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PERIPHERAL AUDITORY DISPLAY FOR 3D-PRINTING PROCESS MONITORING

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ABSTRACT

When monitoring an industrial process, extreme sensory conditions can make it difficult to rely solely on direct observation. In this paper, we describe the development of an alternative display method for the production criteria of a wire-arc 3D-printing process using sonification. We made this display mostly ambient, as it is preferable in order to avoid fatigue in long-term usage. The sounds were chosen to be cognitively distinct progressive alarms so they would be easier to identify. The evaluation consists in a dual-task identification trial, so as to measure the proper communication of critical information as well as account for the level of distraction from other tasks. The results show that the attentional pull is rather minor and still allows for above-random criteria recognition rates. Though, there seems to be an occasional cognitive overlap between the sounds representing local and global overheating. The droning tone for the height of the part also tends to be drowned out in some cases. Both flaws will need to be addressed in future iterations.

1. INTRODUCTION

Despite considerable progress in the automation of industrial processes, a human presence still tends to be required to monitor the machines. This monitoring task can usually be carried out via simple visual observation. However, in practice, visual attention is not always guaranteed as operators may be distracted or focused on other more active tasks. Additionally, an industrial working context is likely to be too unfriendly on the senses to allow for direct observation.

Hearing tends to be more versatile and better adapted to perceiving changes over time than vision, while not requiring constant focus [1]. This makes it a suitable modality for real-time process monitoring by users faced with visually overwhelming working conditions [2–5], in order to avoid the pitfall of inattention blindness [6,7].

Such auditory displays of data can be achieved through

sonification, a data-driven, non-verbal sound [8], usually produced through algorithmic processes in a "systematic, objective and reproducible" way [9]. The use of sonification for monitoring has been a subject of research for many years, in domains as varied as surgical gestures [10, 11], vital signs [12], business processes [13–15], internet activity [16–19], algorithmic processes [20], or domestic activity [21,22].

While developing our sonification for a manufacturing process, we want to avoid the "better safe than sorry" approach of using sudden and loud alarms, as pointed out by Patterson et al. [23] and Lazarus et al. [24]. Instead we need a continuous sound that can be relegated to the background of other activities and evolve into a notification when necessary. This type of notification system is known as a peripheral display, or an ambient information system [25].

Our goal in this paper is to construct and evaluate a peripheral sonification prototype for the monitoring of an industrial 3D-printing process. As this work is still in an early stage of development, the evaluation will be conducted in a simulated work context rather than in-situ. We start by describing the process to be sonified as well as its use context. We then analyse the existing methodology regarding the design and evaluation of peripheral displays, before describing our prototype and its dual-task evaluation process. From the results, we assess ways to improve the sounds used.

2. 3D-PRINTING PROCESS

The process to be monitored is a wire-arc 3D-printing process [26]. Operators for those machines need to be able to detect anomalies in five criteria: the local width, height, and temperature monitored at the position of the printing head, and the global height and temperature along the part being constructed. See also [15].

The printing takes place inside an inert atmosphere to prevent chemical reactions that may impair the material's properties. Unfortunately, this precaution gets in the way of the operator's visual inspection. The wire-arc process emits flashing lights and projections, so operators have to wear protective masks which also greatly narrow down their fields of vision. Thus it is only really convenient to visually check the production during the cooling phases

1 between each layer. Even then, the discrepancies to be noticed in the geometry are usually smaller than a few millimeters, and the temperature cannot be assessed visually most of the time.

2 For these reasons, there has been an effort in the last few years towards augmenting reality for manufacturing processes using alternative display methods [15, 27–30] such as, in the case of this work, sonification for wire-arc 3D-printing.

3 We notice that, to some extent, the sounds of manufacturing already provide some insight into defects that may be occurring during the printing process, such as the noise grains becoming more distinct in case of a lower weld pool, or the sound stopping entirely in case of a material shortage. However, that sound is overall loud and unpleasant, as well as potentially dangerous for hearing upon prolonged exposure. Thus operators wear noise-reducing headphones to protect their ears. Our aim is to put those headphones to good use by having them output an auditory display designed to help monitor the process.

3. RELATED WORKS

3.1 Peripheral Displays

4 In 1985, Jenkins saw the potential in the hearing modality for information communication in ambient contexts [1]. The concept of ambient or peripheral displays then rose in popularity in the late 1990s and early 2000s with the arrival of ubiquitous computing and calm technologies announced by Weiser & Brown in 1996 [31]. In 1998, Wisneski et al. offered an early review on the topic, while calling for more research into ambient information technologies [32].

5 Such research took place in the 2000s in an effort to boil down the main criteria for the design of a peripheral display based on its goals and use context. McCrickard et al. [33] define 3 criteria: interruption, reaction and comprehension. Matthews et al.'s criteria [34] relate more to the way a notification should appear in one's field of attention: abstraction, notification level and transition. Pousman and Stasko [25] give 4 criteria: information capacity, notification level, representational fidelity and aesthetic emphasis. A few nuances aside, all these criteria can be roughly aggregated into the following list of considerations, which we used to better define the scope of our display:

- 6 • Information capacity: How many dimensions of data does the display need to account for? Here we have 5 dimensions (the weld pool's width, height, temperature, and the part's height and temperature). For all of those dimensions except the part's temperature, users should also be able to recognize the direction of the anomaly.
- 7 • Information abstraction: How precisely should users be able to reconstruct the data from the display? Here, there is no need for exact values but users need to know which dimensions are behaving abnormally, in which directions, and whether those anomalies should be considered critical.

- 8 • Notification levels: How does the degree of urgency evolve according to the type of information being conveyed? Here we want a subtle progression of the sounds following data fluctuations, so that a slight change in a dimension, without necessarily being detrimental to the production in itself, can preemptively catch the user's attention for the potential arrival of a bigger shift.

- 9 • Aesthetic emphasis: How pleasant should the display be? So far, the criteria for our work seem to relate it to what Pousman et al. call an "information monitor display", for which aesthetics are of rather low priority [25]. Though, since users would be listening to that sound repeatedly and over prolonged periods of time, we still feel it is necessary to make it pleasant enough to not become stressful.

3.2 Evaluation Methodology

10 A few different approaches can be taken to evaluate a peripheral display. Eventually, the best way is to put the display to use directly in its intended context by means of an in-situ implementation [22, 35]. Although, in early design stages, this is not always possible or suitable, either from a lack of equipment or because the display is still too experimental to be representative of what the intended audience may expect.

11 In a lot of situations, simply asking users to assess their experience through interviews and surveys is enough to gather information about the aesthetic value and intrusiveness of a display [36–40]. This is sufficient when the display's intended use is to be part of a relaxing augmented environment for the house, workplace, or public spaces.

12 Additionally, in cases where the display needs to convey more critical information, the evaluation also has to account for the intelligibility of that information. This requires more quantifiable data on users' performance when using the display, which are usually obtained by means of identification trials [15, 41, 42].

13 When a critical information display is intended to be part of a larger work context, a measurement of distraction is also needed. McCrickard et al. recommend a dual-task evaluation process to this end [33]. This methodology has also been researched more recently by Hausen et al. [43], Daniel [44], and it was implemented in several experiments on peripheral auditory displays [19, 21, 45–49].

14 In the case of our work, in-situ implementation is not feasible yet, as no sensors are actually present on the printers to provide the critical data to be monitored. Still, our goal is to produce a display that will help monitor the process with no need for direct exposure. This requires us to take into account other activities that would be made possible by this newfound sensory freedom, such as for example "checking one's e-mail" or "preparing the next print". Thus, our experiment will not only account for data intelligibility, but also for attentional capture through the use of a dual-task identification trial.

4. MAPPING CHOICES

Soundscapes of several simultaneous sound streams have been shown to facilitate the identification of multidimensional data [12, 47, 49–51] so we chose to convey our data using a soundscape of four perceptually and cognitively distinct sounds streams. The natural world offers many audible phenomena that can be metaphorically related to temperature (boiling, sizzling, exploding, crackling), but not that many when it comes to hearing the dimensions of an object. So, although we can afford to symbolically represent temperature with temperature-related auditory icons [52], the display of geometry requires a more abstract representation. For our display, we chose musical parameters. We expect that using sounds of such different natures will help quickly identify which one is behaving abnormally. Following is a description of how each sound stream is constructed and mapped to its corresponding criterion.

The geometric criteria (part height, weld pool width and weld pool height) are conveyed by continuous streams of structured, repetitive musical notes. It is preferable that those notes follow western rules of musical intervals, as they are easier to identify for European listeners [53], and are commonly considered more pleasant to listen to than atonal or noisy sounds. In the absence of anomalies, those notes constitute a baseline sound confirming that the sonification is up and running. As anomalies arise though, their fluctuations should induce a feeling of slight unease in the listeners, thus prompting reaction [54].

For the local weld pool dimensions, a lead arpeggio (L) of 3 notes in the chord of C major keeps playing as long as the dimensions are within bounds. This repetitive sequence of notes serves as a metaphor for droplets of matter being deposited during printing. The timbre for this sound is the default SuperCollider synth: a basic piano-like sound. The width influences the duration of those notes (inverse polarity mapping between 0.5 and 1.5 seconds). The height is conveyed by the starting pitch of the sequence (between C5 and F6). Loudness is also influenced by an amplitude factor, computed as the mean of two values respectively mapped to width and height anomalies (each between 0.02 and 0.2). We expect this sound to stand out in case of an anomaly by becoming faster, louder, and more erratic as the dimensions diverge from the norm.

For the relative part height (difference between the expected height and the current height), a continuous droning synthetic tone (D) varies in pitch (notes between E2 and D3). The absolute value of the height difference is conveyed by an amplitude factor mapped between 0.1 and 0.4. This continuous sound serves as a metaphor for the continuity of horizontal layers, with pitch fluctuations representing irregularities in a layer. The timbre for this sound is constructed as a sawtooth wave, bandpass-filtered around its first and second harmonics with each filtered harmonic playing in the left and right ear respectively.

Meanwhile, the thermal criteria (weld pool temperature and part temperature) are conveyed by noisy pre-recorded natural sounds that emerge in case of anomalies but remain silent otherwise. We elected to use the sounds of water re-

acting to heat and cold as they constitute an easily identifiable everyday metaphor for temperature in the system, and their noisy nature makes them stand out against the tonal background.

The weld pool temperature, when below its ideal value, is conveyed by the sound of crackling ice (W-). A temperature over the ideal value is conveyed by the sound of boiling water (W+). Straying further from the accepted range influences a gain factor mapped between 0 and 0.9, then rescaled and graduated as:

$$Gain = \begin{cases} 0 & \text{if } 0 \leq Gain \leq 0.4 \\ 0.2 & \text{if } 0.4 < Gain \leq 0.6 \\ 0.5 & \text{if } 0.6 < Gain \leq 0.9 \end{cases} \quad (1)$$

Thus this sound stream is inaudible as long as the temperature is within bounds, and only emerges as it turns into an anomaly.

Finally, when the global temperature of the part passes its threshold of 600°C, the sudden sound of sizzling water (S) is triggered.

The pitch, speed and loudness ranges for those sounds were chosen as a consequence of our previous work on the same project [15], which resulted in the participants requesting lower, slower and overall more distant sounds.

In the following sections, anomalies will be referred to by the first letter of their sound elements. For instance, the combination of lead arpeggio, drone, and boiling water anomalies will be called LDW+.

5. EXPERIMENT

5.1 Process

The primary task of our dual-task evaluation is based on the one described in [44]. It consists in copying random sequences of 'X' and 'O' symbols, whose lengths are randomly picked between 2 and 5. Participants interact with this game by clicking elements of a graphical user interface. As soon as a sequence has been copied, another one is generated and displayed, prompting the participants to copy as many sequences as they can in the duration of each level. We chose this very simple primary task because it gives an easily quantifiable assessment of the participants' performance while not relying too heavily on any one's individual abilities.

Simultaneously, the secondary task consists in listening and labelling sounds in real time by checking the corresponding boxes in the interface. See Figure 1. Those boxes are labelled after the types of sounds conveying the anomalies: "Lead", "Drone", "Water" and "Sizzle". W+ and W- are fused into a single box in the interface, simply labelled "Water" as, for now, the evaluation is more focused on the recognition of the anomalies than their polarities.

Before getting to the evaluation itself, players go through a progressive training phase during which they learn to copy sequences, then to recognize sounds, and finally to carry out both tasks at the same time. This training can be redone as many times as the player deems necessary. Still, players have to get a labelling score of 90% or higher

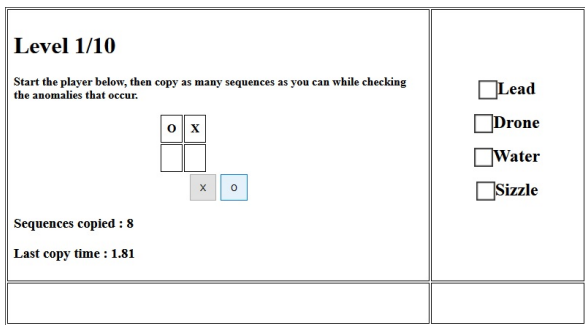


Figure 1. A screen capture of the experiment interface during a level. In the middle, the player rewrites the sequence displayed by clicking the 'X' and 'O' buttons in the same order. Upon each sequence completion, a new one appears. Boxes on the right allow the player to point out anomalies as he or she notices them.

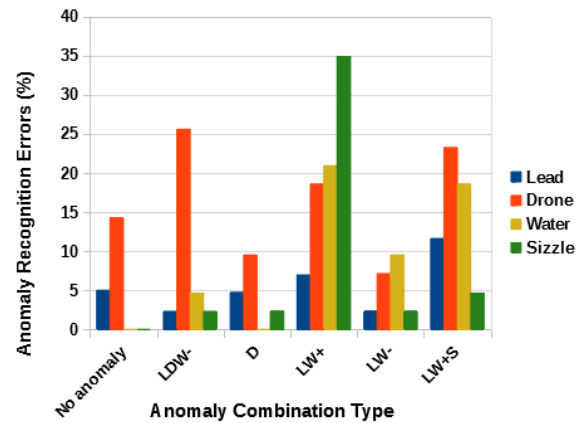


Figure 2. Mean error rate for the identification of anomalies, for each anomaly type (colors) and for each anomaly combination (horizontal sections).

1 in the last phase of that training before they can start the
2 evaluation.

3 This evaluation interface can still be accessed online ¹,
4 but it does not record entries anymore.

5 5.2 Data

6 We used pre-simulated data recorded in .csv files repre-
7 senting various printing scenarios. Our data were sonified
8 into .wav files according to the mapping choices described
9 in Section 4 using a SuperCollider ² script. In those sim-
10 ulations, the only anomaly combinations encountered are
11 the ones that are likely to occur according to the way cri-
12 teria physically interact (e.g. a higher local temperature
13 causes the weld pool to spread out more, thus becoming
14 lower and wider). This gives us 8 possible combinations,
15 including the regular anomaly-free behaviour. Three of
16 those were selected for the training phase and presented in
17 this order: LD, LDW+, and no anomaly. All other anomaly
18 combinations available were used for the experiment in a
19 randomized order: LDW-, D, LW+, LW-, LW+S, and five
20 more situations with no anomaly.

21 5.3 Participants

22 43 participants took part in the experiment: 20 M, 23 F,
23 aged from 18 to 67 (average 32). By taking part in the ex-
24 periment, participants certified that their hearing was unal-
25 tered. Five of them had taken part in an earlier experiment
26 for the same project and were familiar with some of the
27 mapping choices.

28 6. RESULTS

29 We measured participants' performance at the primary task
30 by recording the length and time of completion of each se-
31 quence copied. For the secondary task, we recorded the
32 times at which anomaly boxes were checked. After the

¹ <https://maxime-poret.emi.u-bordeaux.fr/these/eval2020/> - Accessed 3/12/21

² <https://supercollider.github.io/> - Accessed 3/12/21

33 experiment, participants were given the option to also an-
34 swer a short survey on the aesthetics and intrusiveness of
35 the display.

36 6.1 Anomaly identification

37 For each type of level, we computed the error rate for
38 anomaly identification, such that a criterion was consid-
39 ered inaccurately identified when its box was checked de-
40 spite there being no anomaly, or unchecked despite the
41 presence of an anomaly. Those results are displayed in
42 Figure 2. We find it encouraging that all criteria were
43 recognized above random chance, as it is likely that with
44 more training testers would be able to identify all anom-
45 alies more accurately. Still, the most frequent errors high-
46 light which parts of the display can be made clearer in fu-
47 ture iterations.

48 D seems to be the most difficult anomaly to label as its
49 error rate is the highest in 4 levels out of 6. For levels
50 LW+, LW-, LW+S, and no anomaly, false positives may
51 be due to the fact that people start expecting D for every
52 anomaly combination, as it is often linked to others and is
53 present in most of the training levels. In levels LDW- and
54 D, false negatives may be due to the fact that the drone is
55 more subtle than the other sounds, and can be more easily
56 tuned out or drowned out. Both false positives and false
57 negatives seem to indicate that the drone sound is not no-
58 ticeable enough for some testers, who instead choose to
59 respond seemingly "at random".

60 We also notice that, in the level LW+, the sound of boil-
61 ing water was sometimes mistaken for the sizzle, which re-
62 sulted in 35% of testers checking that box. During LW+S,
63 the sizzle was mostly recognized but some participants ne-
64 glected the L and W+ anomalies also occurring at the same
65 time.

66 6.2 Attentional curves

67 We computed the attentional curves for each type of level
68 as the average symbol-copying speed of participants over
69 the course of a level. On the same time scale, we also
70 plotted the anomaly onsets and average labelling times as

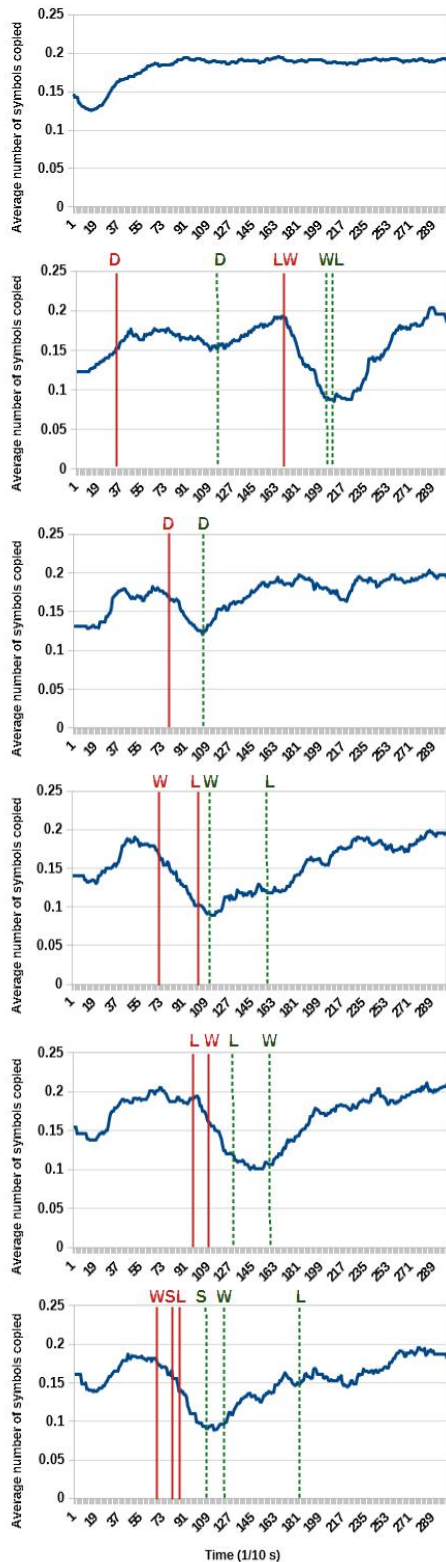


Figure 3. Attentional curves for each level type in the evaluation, computed as the average number of symbols copied for each decisecond. Red lines: onset times of the anomalies. Green dotted lines: mean annotation time. Level types from top to bottom: No Anomaly, LDW-, D, LW+, LW-, LW+S

1 timestamps of the attentional capture of the participants.
2 See Figure 3.

3 In levels with no anomaly, users get gradually more ef-
4 ficient at the primary task as their copying speed reaches
5 a limit of 0.2 symbols per decisecond after 8 seconds. A
6 similar dynamic can be observed at the start of the other
7 types of levels, but with an efficiency drop of approxi-
8 mately 0.1 symbols per decisecond when an anomaly is
9 triggered. Participants do not seem to have issues recover-
10 ing once they have reacted, since by the end of each level
11 the average copying speed returns to the limit of 0.2 ob-
12 served in levels with no anomaly. Recovery appears to take
13 more or less time depending on the number of onsets, their
14 distribution in time and their durations.

15 In the LDW- level, the anomaly onset for D did not af-
16 fect participants' performance as much as the anomalies in
17 most levels (about 0.03 symbols per decisecond instead of
18 0.1). Although it was still noticed on average before L and
19 W- started playing, it took longer to be labelled than most
20 of the anomalies. This may be due to the fact that, in that
21 level, the drone's pitch starts slowly lowering before any
22 other anomaly is triggered, which may be more difficult to
23 perceive than faster changes, or a rising pitch.

24 In the LW+S level, although W+, S and L were triggered
25 in this order with delays of 1 second between each, S was
26 the first one to be attended to on average, possibly due to
27 its more startling nature and its relative rareness in the ex-
28 periment.

29 6.3 Survey

30 After testing the display, 21 of the participants also an-
31 swered a survey about their experience. In the survey,
32 they were presented with a series of sentences regarding
33 the experiment, which they could rate on a scale from 1
34 (disagree) to 3 (agree), 2 being a neutral response. 18 par-
35 ticipants (85.7%) disagreed with the sentence "The sound
36 bothered me while doing the task", while the rest remained
37 neutral. On the sentence "I found the sound to be stressful",
38 14 participants (66.7%) disagreed, 6 (28.6%) remained
39 neutral, and 1 (4.8%) agreed. These answers suggest that
40 the sound was not perceived as overly intrusive by testers,
41 but that its aesthetics, especially when it comes to inducing
42 stress, could be more polished. A more formal evaluation
43 of these rather qualitative properties of the display is still
44 to be produced.

45 7. CONCLUSION

46 We produced an auditory display for an industrial process
47 that does not allow for direct visual monitoring. This dis-
48 play is intended to be minimally-intrusive and aesthetically
49 pleasing. The sound streams were chosen in a way that
50 should make them easily identifiable and relatable to the
51 criteria they represent. We evaluated this display with a fo-
52 cus on both the attentional pull and the intelligibility of the
53 information.

54 Our experiment shows that there is an overlap between
55 the sounds of sizzle and boiling water that makes it more
56 difficult for users to distinguish them when they are pre-

1 sented separately. In expected use scenarios, though, the
2 sizzle sound is mostly intended as a last resort alert. In-
3 deed, it should not occur very often and the sound of boil-
4 ing should have already been playing for a good amount of
5 time when the sizzle happens. We find it encouraging that,
6 although both sounds were not perfectly discriminated,
7 most testers definitely recognized overheating alerts.

8 We also find that when the drone’s pitch goes downward
9 too slowly, it is harder to notice as an anomaly, so a linear
10 mapping of relative height to pitch alone may not be the
11 most suitable choice. We could make this sound stream
12 more alerting by having another timbre emerge when the
13 part height passes its tolerated threshold.

14 The brief evaluation process we implemented gives us in-
15 sight into flaws that can be addressed in future iterations of
16 the prototype, but it would also be interesting to know how
17 many of the reoccurring mistakes would still be made after
18 a longer training period, possibly over several sessions.

19 Predictably, most anomaly onsets cause the attention for
20 the primary task to drop, but participants are still able to
21 recover rather quickly. It is worth noting that not everyone
22 takes the same amount of time to move their mouse be-
23 tween the two areas of the screen. This adds a bias to our
24 computation of attention which we could have measured
25 in an early step of the experiment (for instance by timing
26 testers clicking back and forth between those areas) and
27 accounted for in the results.

28 Sound ecology is an important aspect of auditory moni-
29 toring [55] that we wish could have been more thoroughly
30 taken into account in both the design and evaluation of the
31 display. Indeed, despite the use of noise-reducing head-
32 phones, it is unlikely that the noise of production will be
33 entirely suppressed, which may get in the way of some of
34 the sounds we chose. Also, due to the sanitary conditions
35 at the time of testing, the evaluation was presented as a
36 webpage sent out to participants, who all played it at home
37 on their own setups and using their own sound gear. For
38 those reasons, we look forward to experimenting in better
39 standardized conditions in the future.

40 Once improved for optimal recognition rates, this display
41 is intended to be put to use in further experimentation on
42 integrating sonification into an augmented work context,
43 putting operators in simulated printing sessions where the
44 criteria are displayed through both sound and touch.

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