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► **To cite this version:**

Maxime Poret, Sébastien Ibarboure, Catherine Semal, Myriam Desainte-Catherine, Nadine Couture. PERIPHERAL AUDITORY DISPLAY FOR 3D-PRINTING PROCESS MONITORING. 2021 Sound and Music Computing Conference, SMC 2021, Jun 2021, Torino, Italy. hal-03618071

HAL Id: hal-03618071

<https://hal.science/hal-03618071>

Submitted on 24 Mar 2022

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PERIPHERAL AUDITORY DISPLAY FOR 3D-PRINTING PROCESS MONITORING

Maxime PORET (maxime.poret@labri.fr)¹, Sébastien IBARBOURE (s.ibarboure@estia.fr)²,
Catherine SEMAL (catherine.semal@ensc.fr)³, Myriam DESAINTE-CATHERINE (myriam@labri.fr)¹, and
Nadine COUTURE (n.couture@estia.fr)²

¹Univ. Bordeaux, Bordeaux INP, CNRS, LaBRI, UMR5800, F-33400 Talence, France

²Univ. Bordeaux, ESTIA Institute of Technology, LaBRI, UMR5800, F-64210 Bidart, France

³Univ. Bordeaux, Bordeaux INP, CNRS, INCIA, UMR5287, F-33076 Bordeaux, France

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 [1–3]. This makes it a suitable modality for real-time process monitoring by users faced with visually overwhelming working conditions [4–7], in order to avoid the pitfall of inattentive blindness [8–10].

Such auditory displays of data can be achieved through

sonification, a data-driven, non-verbal sound [11], usually produced through algorithmic processes in a "systematic, objective and reproducible" way [12]. The use of sonification for monitoring has been a subject of research for many years, in domains as varied as surgical gestures [13, 14], vital signs [15], business processes [16–21], internet activity [22–25], algorithmic processes [26], or domestic activity [27, 28].

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. [29] and Lazarus et al. [30]. 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 [31].

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-tasking 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 [32]. 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 [21].

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 no- 58
2 ticed in the geometry are usually smaller than a few mil- 59
3 limeters, and the temperature cannot be assessed visually 60
4 most of the time. 61

5 For these reasons, there has been an effort in the last few 62
6 years towards augmenting reality for manufacturing pro- 63
7 cesses using alternative display methods [21, 33–36] such 64
8 as, in the case of this work, sonification for wire-arc 3D- 65
9 printing.

10 We notice that, to some extent, the sounds of manufac- 66
11 turing already provide some insight into defects that may 67
12 be occurring during the printing process, such as the noise 68
13 grains becoming more distinct in case of a lower weld pool, 69
14 or the sound stopping entirely in case of a material short- 70
15 age. However, that sound is overall loud and unpleasant, as 71
16 well as potentially dangerous for hearing upon prolonged 72
17 exposure. Thus operators wear noise-reducing headphones 73
18 to protect their ears. Our aim is to put those headphones to 74
19 good use by having them output an auditory display de- 75
20 signed to help monitor the process.

21 3. RELATED WORKS

22 3.1 Peripheral Displays

23 In 1985, Jenkins saw the potential in the hearing modal- 81
24 ity for information communication in ambient contexts [3]. 82
25 The concept of ambient or peripheral displays then rose in 83
26 popularity in the late 1990s and early 2000s with the arrival 84
27 of ubiquitous computing and calm technologies announced 85
28 by Weiser & Brown in 1996 [37]. In 1998, Wisneski et al. 86
29 offered an early review on the topic, while calling for more 87
30 research into ambient information technologies [38]. 88

31 Such research took place in the 2000s in an effort to boil 89
32 down the main criteria for the design of a peripheral dis- 90
33 play based on its goals and use context. Summarized below 91
34 are the ways those papers helped us better define the scope 92
35 of our display. 93

36 McCrickard et al. [39] give 3 criteria: interruption, reac- 94
37 tion and comprehension. As our goal is to provide a dis- 95
38 play for critical activity monitoring, the levels of priority 96
39 for these criteria should all be high. Indeed an operator 97
40 should be able to notice an anomaly and react accordingly 98
41 in a minimal amount of time. We note that our focus here is 99
42 on the identification of the anomalies rather than on read- 100
43 ing any actual value from the display, so comprehension 101
44 priority, although high, is perhaps not maximal. 102

45 Matthews et al.’s set of criteria relates more to the way a 103
46 notification should appear in one’s field of attention [40]: 104
47 abstraction, notification level and transition. In our case, 105
48 information is definitely abstracted, as we want the display 106
49 to communicate anomalous progressions in the data with 107
50 no need for a precise value. We also want to communi- 108
51 cate these progressions in varying degrees of urgency, as a 109
52 slight change in itself may not be detrimental to the pro- 110
53 duction, but should preemptively catch the user’s attention 111
54 for the potential arrival of a bigger shift. 112

55 Pousman and Stasko [31] give 4 criteria: information ca- 113
56 pacity, notification level, representational fidelity and aes- 114
57 thetic emphasis. Our work is similar to what these authors

refer to as an "information monitor display". For this type 58
of display, we should prioritize information capacity (dis- 59
play all five data dimensions) and notification level (vary- 60
ing degrees of urgency). The representational fidelity is 61
of medium priority (no need for exact values) and the aes- 62
thetic emphasis is rather low. Here, part of our efforts will 63
still be directed toward making the sound pleasant enough 64
to not become stressful. 65

66 3.2 Evaluation Methodology

67 A few different approaches can be taken to evaluate a pe- 68
69 ripheral display. Eventually, the best way is to put the dis- 70
71 play to use directly in its intended context by means of an 72
73 in-situ implementation [28, 41]. Although, in early design 74
75 stages, this is not always possible or suitable, either from a 76
77 lack of equipment or because the display is still too exper- 78
79 imental to be representative of what the intended audience 80
81 may expect.

82 In a lot of situations, simply asking users to assess their 83
84 experience through interviews and surveys is enough to 85
86 gather information about the aesthetic value and intrusive- 87
88 ness of a display [42–47]. This is sufficient when the dis- 89
90 play’s intended use is to be part of a relaxing augmented 91
92 environment for the house, workplace, or public spaces. 93

94 Additionally, in cases where the display needs to con- 95
96 vey more critical information, the evaluation also has to 97
98 account for the intelligibility of that information. This re- 99
99 quires more quantifiable data on users’ performance when 100
101 using the display, which are usually obtained by means of 102
103 identification trials [21, 48, 49].

104 When a critical information display is intended to be part 105
106 of a larger work context, a measurement of distraction is 107
108 also needed. McCrickard et al. recommend a dual-task 109
110 evaluation process to this end [39]. This methodology has 111
112 also been researched more recently by Hausen et al. [50], 113
114 Daniel [51], and it was implemented in several experiments 115
116 on peripheral auditory displays [19, 25, 27, 52–55].

117 In the case of our work, in-situ implementation is not fea- 118
119 sible yet, as no sensors are actually present on the print- 119
120 ers to provide the critical data to be monitored. Still, our 120
121 goal is to produce a display that will help monitor the pro- 121
122 cess with no need for direct exposure. This requires us to 122
123 take into account other activities that would be made pos- 123
124 sible by this newfound sensory freedom, such as for exam- 124
125 ple "checking one’s e-mail" or "preparing the next print". 125
126 Thus, our experiment will not only account for data intelli- 126
127 gibility, but also for attentional capture through the use of 127
128 a dual-task identification trial.

129 4. MAPPING CHOICES

130 Soundscapes of several simultaneous sound streams have 131
132 been shown to facilitate the identification of multidimen- 133
134 sional data [15, 19, 54, 56, 57] so we chose to convey our 134
135 data using a soundscape of four perceptually and cogni- 135
136 tively distinct sounds streams. This consisted in select- 136
137 ing an array of sounds that each evokes a different sound- 137
138 producing situation. Those metaphors were chosen in a 138
139 way that, we expect, also facilitates the classification of 139
140

1 sounds according to the properties of the anomalies they
2 represent.

3 As such, the geometric criteria (part height, weld pool
4 width and weld pool height) are conveyed by continuous
5 streams of structured, repetitive musical notes. It is prefer-
6 able that those notes follow western rules of musical in-
7 tervals, as they are easier to identify for european listen-
8 ers [58], and are commonly considered more pleasant to
9 listen to than atonal or noisy sounds. In the absence of
10 anomalies, those notes constitute a baseline sound confirm-
11 ing that the sonification is up and running. As anomalies
12 arise though, their fluctuations should induce a feeling of
13 slight unease in the listeners, thus prompting reaction [59].

14 For the local weld pool dimensions, a lead arpeggio (L)
15 of 3 notes in the chord of C major keeps playing as long
16 as the dimensions are within bounds. The width influences
17 the duration of those notes (inverse polarity mapping be-
18 tween 0.5 and 1.5 seconds). The height is conveyed by the
19 starting pitch of the sequence (between C5 and F6). Loud-
20 ness is also influenced by an amplitude factor, computed as
21 the mean of two values respectively mapped to width and
22 height anomalies (each between 0.02 and 0.2). We expect
23 this sound to become faster, louder, and more erratic as the
24 dimensions diverge from the norm.

25 For the relative part height (difference between the ex-
26 pected height and the current height), a continuous dron-
27 ing synthetic tone (D) varies in pitch (notes between E2
28 and D3). The absolute value of the height difference is
29 conveyed by an amplitude factor mapped between 0.1 and
30 0.4. This way, the drone gets louder as the part height di-
31 verges while its pitch fluctuations indicate whether it is too
32 tall or too short.

33 Meanwhile, the thermal criteria (weld pool temperature
34 and part temperature) are conveyed by noisy pre-recorded
35 natural sounds that emerge in case of anomalies but re-
36 main silent otherwise. We elected to use the sounds of
37 water reacting to heat and cold as they constitute an eas-
38 ily identifiable everyday metaphor for temperature in the
39 system [60, 61]. Their noisy nature makes them stand out
40 against the tonal background.

41 The weld pool temperature, when below its ideal value,
42 is conveyed by the sound of crackling ice (W-). A tem-
43 perature over the ideal value is conveyed by the sound of
44 boiling water (W+). Straying further from the accepted
45 range influences an amplitude factor (computed between
46 0 and 0.9 and graduated as: $[0.0, 0.4] \rightarrow 0;]0.4, 0.6] \rightarrow$
47 $0.2;]0.6, 0.9] \rightarrow 0.5$). Thus this sound stream is inaudi-
48 ble as long as the temperature is within bounds, and only
49 emerges as it turns into an anomaly.

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

53 The pitch, speed and loudness ranges for those sounds
54 were chosen as a consequence of our previous work on
55 the same project [21], which resulted in the participants
56 requesting lower, slower and overall more distant sounds.

57 In the following sections, anomalies will be referred to
58 by the first letter of their sound elements. For instance,
59 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 [51]. It consists in copying random
sequences of 'X' and 'O' symbols, whose lengths are ran-
domly picked between 2 and 5. Participants interact with
this game by clicking elements of a graphical user inter-
face. 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 in-
dividual abilities.

Simultaneously, the secondary task consists in listening
and labelling sounds in real time by checking the corre-
sponding boxes in the interface. See Figure 1. Those boxes
are labelled after the types of sounds conveying the anom-
alies: "Lead", "Drone", "Water" and "Sizzle". W+ and W-
are fused into a single box in the interface, simply labelled
"Water" as they convey the same variable whose polarity is
considered secondary information for now.

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

This evaluation interface can still be accessed online¹,
but it does not record entries anymore.

5.2 Data

We used pre-simulated data recorded in .csv files repre-
senting various printing scenarios. Our data were soni-
fied into .wav files according to the mapping choices de-
scribed in Section 4 using a script written for SuperCol-
lider². In the simulations we are working with, the only
anomaly combinations encountered are the ones that are
likely to occur according to the way criteria physically in-
teract (for instance: a higher local temperature causes the
weld pool to spread out more, thus becoming lower and
wider). This gives us 8 possible combinations, including
the regular anomaly-free behaviour. Three of those were
selected for the training phase and presented in this order:
LD, LDW+, and no anomaly. All other anomaly combina-
tions available were used for the experiment in a random-
ized order: LDW-, D, LW+, LW-, LW+S, and five more
situations with no anomaly.

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

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

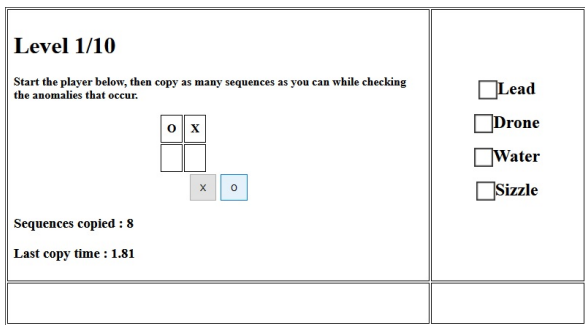


Figure 1. A screen capture of the experiment interface during a level. In the middle, the player clicks the buttons to copy the sequence displayed. Boxes on the right allow the player to point out anomalies as he or she notices them.

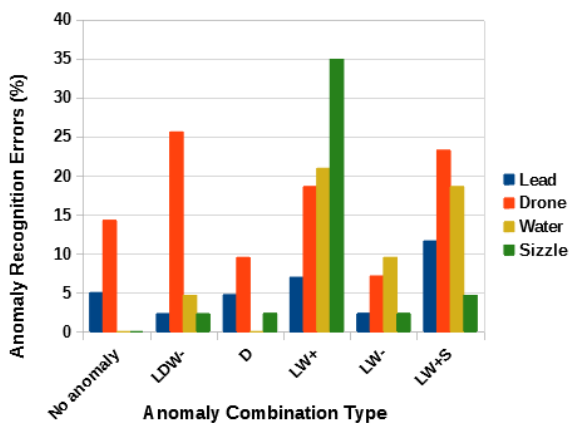


Figure 2. Mean error rate for the identification of anomalies, for each anomaly type (colors) and for each anomaly combination (horizontal sections).

5.3 Participants

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

6. RESULTS

We measured participants' performance at the primary task by recording the length and time of completion of each copied sequence. For the secondary task, we recorded the times at which anomaly boxes were checked.

6.1 Anomaly identification

For each type of level, we computed the error rate for anomaly identification, such that a criterion was considered inaccurately identified when it was checked despite there being no anomaly, or unchecked despite the presence of an anomaly. Those results are displayed in Figure 2. Our soundscape's overall performance seems to be rather good, as all criteria were accurately identified above random chance by testers.

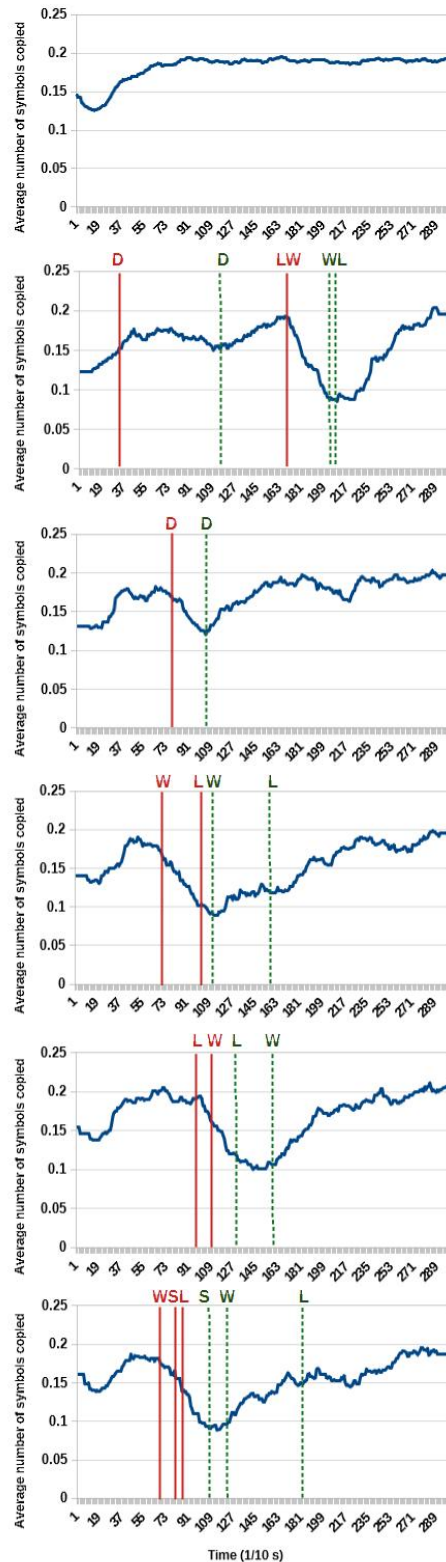


Figure 3. Attentional curves for each level type in the evaluation, computed as the average number of symbols copied for each decisecond. Red lines: onset times of the anomalies. Green dotted lines: mean annotation time. Level types from top to bottom: No Anomaly, LDW-, D, LW+, LW-, LW+S

1 Still, D seems to be the most difficult anomaly to label as 57
2 its error rate is the highest in 4 levels out of 6. For levels 58
3 LW+, LW-, LW+S, and no anomaly, false positives may 59
4 be due to the fact that people start expecting D for every 60
5 anomaly combination, as it is often linked to others and is 61
6 present in most of the training levels. In levels LDW- and 62
7 D, false negatives may be due to the fact that the drone is 63
8 more subtle than the other sounds, and can be more easily 64
9 tuned out or drowned out. Both false positives and false 65
10 negatives seem to indicate that the drone sound is not notice- 66
11 able enough for some testers, who instead choose to 67
12 respond seemingly "at random". 68

13 We also notice that, in the level LW+, the sound of boil- 69
14 ing water was sometimes mistaken for the sizzle, which re- 70
15 sulted in 35% of testers checking that box. During LW+S, 71
16 the sizzle was mostly recognized but some participants ne- 72
17 glected the L and W+ anomalies also occurring at the same 73
18 time. 74

19 6.2 Attentional curves 75

20 We computed the attentional curves for each type of level 76
21 as the average symbol-copying speed of participants over 77
22 the course of a level. On the same time scale, we also 78
23 plotted the anomaly onsets and average labelling times as 79
24 an indicator of the attentional capture of the participants. 80
25 See Figure 3. 81

26 In levels with no anomaly, users get gradually more ef- 82
27 ficient at the primary task as their copying speed reaches 83
28 a limit of 0.2 symbols per decisecond after 8 seconds. A 84
29 similar dynamic can be observed at the start of the other 85
30 types of levels, but with an efficiency drop of approxi- 86
31 mately 0.1 symbols per decisecond when an anomaly is 87
32 triggered. Participants do not seem to have issues recover- 88
33 ing once they have reacted, since by the end of each level 89
34 the average copying speed returns to the limit of 0.2 ob- 90
35 served in levels with no anomaly. Recovery appears to take 91
36 more or less time depending on the number of onsets, their 92
37 distribution in time and their durations. 93

38 In the LDW- level, the anomaly onset for D did not af- 94
39 fect participants' performance as much as the anomalies in 95
40 most levels (about 0.03 symbols per decisecond instead of 96
41 0.1). Although it was still noticed on average before L and 97
42 W- started playing, it took longer to be labelled than most 98
43 of the anomalies. This may be due to the fact that, in that 99
44 level, the drone's pitch starts slowly lowering before any 100
45 other anomaly is triggered, which may be more difficult to 101
46 perceive than faster changes, or a rising pitch. 102

47 In the LW+S level, although W+, S and L were triggered 103
48 in this order with delays of 1 second between each, S was 104
49 the first one to be attended to on average, possibly due to 105
50 its more startling nature and its relative rareness in the ex- 106
51 periment. 107

52 7. CONCLUSION 108

53 We produced an auditory display for an industrial process 109
54 that does not allow for direct monitoring. This display is 110
55 intended to be minimally-intrusive and aesthetically pleas-
56 ing. The sound streams were chosen in a way that should

make them easily identifiable and relatable to the criteria
they represent. We evaluated this display with a focus on
the attentional pull and the intelligibility of the informa-
tion.

Our experiment shows that there is an overlap between
the sounds of sizzle and boiling water that makes it more
difficult for users to distinguish them when they are pre-
sented separately. In expected use scenarios, though, the
sizzle sound is mostly intended as a last resort alert. In-
deed, it should not occur very often and the sound of boil-
ing should have already been playing for a good amount of
time when the sizzle happens. We find it encouraging that,
although both sounds were not perfectly discriminated,
most testers definitely recognized overheating alerts. We
also find that when the drone's pitch goes downward too
slowly, it is harder to notice as an anomaly, so the choice
of a linear mapping of relative height to pitch may not be
the most suitable. Predictably, most anomaly onsets cause
the attention for the primary task to drop, but participants
are still able to recover rather quickly.

Sound ecology is an important aspect of auditory moni-
toring [2] that we wish could have been more thoroughly
taken into account in both the design and evaluation of the
display. Indeed, despite the use of noise-reducing head-
phones, it is unlikely that the noise of production will be
entirely suppressed, which may get in the way of some of
the sounds we chose. Also, due to the sanitary conditions
at the time of testing, the evaluation was presented as a
webpage sent out to participants, who all played it at home
on their own setups and using their own sound gear. For
those reasons, we look forward to experimenting in better
standardized conditions in the future.

Further experimentation on integrating this sonification
into an augmented work context is intended to take place,
putting operators in simulated printing sessions where the
criteria are displayed through both sound and touch.

Acknowledgments

The authors of this paper would like to thank the SCRIME
of the University of Bordeaux for hosting this research, as
well as Matthias Robine and Emmanuel Duc for their in-
volvement in the previous iteration of this work. We would
also like to thank the AddimADOUR program and Anaïs
Domergue for allowing us to observe a wire-arc 3D-printer
in action in February of 2020 and answering our questions.

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