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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 inattentional 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 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.

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.

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

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].

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:

- 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.

- 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.

- 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.

- 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

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.

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.

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].

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].

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 reacting 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 an gain factor mapped between 0 and 0.9, then rescaled and graduated as:

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

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+.

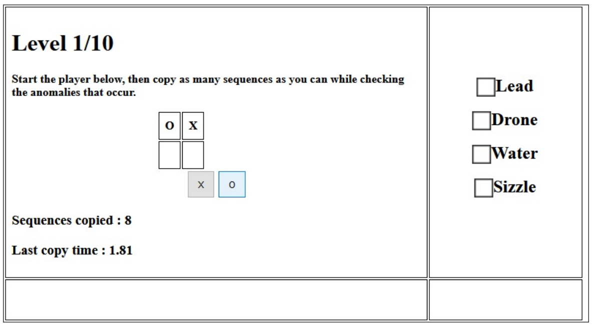
5. EXPERIMENT

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



Level 1/10

Start the player below, then copy as many sequences as you can while checking the anomalies that occur.

Sequences copied : 8

Last copy time : 1.81

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.

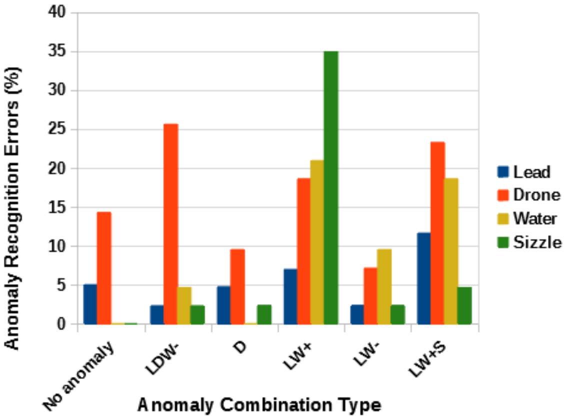


Figure 2. Mean error rate for the identification of anomalies, for each anomaly type (colors) and for each anomaly combination (horizontal sections).

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

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

5.2 Data

We used pre-simulated data recorded in .csv files representing various printing scenarios. Our data were sonified into .wav files according to the mapping choices described in Section 4 using a SuperCollider[2] script. In those simulations, the only anomaly combinations encountered are the ones that are likely to occur according to the way criteria physically interact (e.g. 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 combinations available were used for the experiment in a randomized order: LDW-, D, LW+, LW-, LW+S, and five more situations with no anomaly.

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 sequence copied. For the secondary task, we recorded the times at which anomaly boxes were checked. After the experiment, participants were given the option to also answer a short survey on the aesthetics and intrusiveness of the display.

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 its box was checked despite there being no anomaly, or unchecked despite the presence of an anomaly. Those results are displayed in Figure 2. We find it encouraging that all criteria were recognized above random chance, as it is likely that with more training testers would be able to identify all anomalies more accurately. Still, the most frequent errors highlight which parts of the display can be made clearer in future iterations.

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

We also notice that, in the level LW+, the sound of boiling water was sometimes mistaken for the sizzle, which resulted in 35% of testers checking that box. During LW+S, the sizzle was mostly recognized but some participants neglected the L and W+ anomalies also occurring at the same time.

6.2 Attentional curves

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

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

[2] https://supercollider.github.io/ - Accessed 3/12/21

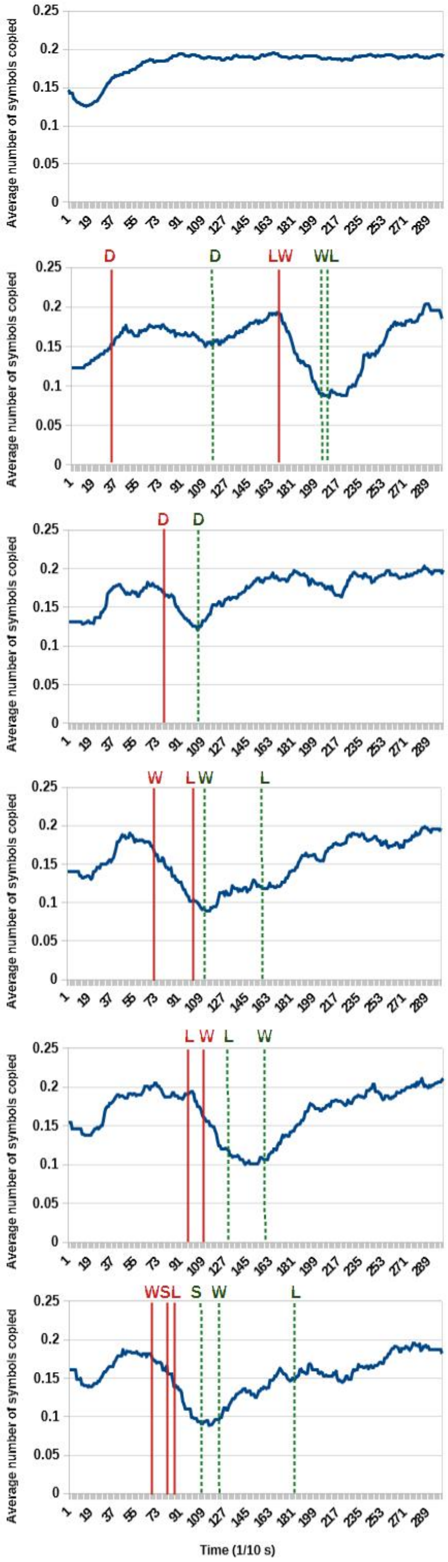

Figure 3. Attentional curves for each level type in the evaluation, computed as the average number of symbols copied for each decisecond. Red lines: onset times of the anomalies. Green dotted lines: mean annotation time. Level types from top to bottom: No Anomaly, LDW-, D, LW+, LW-, LW+S

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

In levels with no anomaly, users get gradually more efficient at the primary task as their copying speed reaches a limit of 0.2 symbols per decisecond after 8 seconds. A similar dynamic can be observed at the start of the other types of levels, but with an efficiency drop of approximately 0.1 symbols per decisecond when an anomaly is triggered. Participants do not seem to have issues recovering once they have reacted, since by the end of each level the average copying speed returns to the limit of 0.2 observed in levels with no anomaly. Recovery appears to take more or less time depending on the number of onsets, their distribution in time and their durations.

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

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

6.3 Survey

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

7. CONCLUSION

We produced an auditory display for an industrial process that does not allow for direct visual monitoring. This display is intended to be minimally-intrusive and aesthetically pleasing. 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 both the attentional pull and the intelligibility of the information.

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 presented separately. In expected use scenarios, though, the sizzle sound is mostly intended as a last resort alert. Indeed, it should not occur very often and the sound of boiling 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 a linear mapping of relative height to pitch alone may not be the most suitable choice. We could make this sound stream more alerting by having another timbre emerge when the part height passes its tolerated threshold.

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

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

Sound ecology is an important aspect of auditory monitoring [55] 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 headphones, 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.

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

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8. REFERENCES

[1] J. J. Jenkins, "Acoustic information for objects, places, and events," in *Persistence and Change: Proceedings of the First International Conference on Event Perception*, W. Warren, Ed. Hilldale, NJ, USA: Lawrence Erlbaum, 1985, pp. 115–138.

[2] J. W. Marcum, "Beyond visual culture: the challenge of visual ecology," *portal: Libraries and the Academy*, vol. 2, no. 2, pp. 189–206, 2002.

[3] S. Oviatt, "Human-centered design meets cognitive load theory: Designing interfaces that help people think," in *Proceedings of the 14th ACM International Conference on Multimedia (MM06)*, Santa Barbara, CA, USA, 2006, pp. 871–880.

[4] Q. Wang, S. Yang, M. Liu, Z. Cao, and Q. Ma, "An eye-tracking study of website complexity from cognitive load perspective," *Decision Support Systems*, vol. 62, pp. 1 – 10, 2014.

[5] J. Zagermann, U. Pfeil, and H. Reiterer, "Measuring cognitive load using eye tracking technology in visual computing," in *Proceedings of the Sixth Workshop on Beyond Time and Errors on Novel Evaluation Methods for Visualization (BELIV '16)*, Baltimore, MD, USA, 2016, pp. 78–85.

[6] R. Marois, D.-J. Yi, and M. M. Chun, "The neural fate of consciously perceived and missed events in the attentional blink," *Neuron*, vol. 41, no. 3, pp. 465–472, 2004.

[7] J. M. Wolfe, T. S. Horowitz, and N. M. Kenner, "Rare items often missed in visual searches," *Nature*, vol. 435, no. 7041, pp. 439–440, 2005.

[8] G. Kramer, B. N. Walker, T. Bonebright, P. Cook, J. H. Flowers, and N. Miner, "The sonification report: Status of the field and research agenda. report prepared for the national science foundation by members of the international community for auditory display," in *International Community for Auditory Display (ICAD)*, Santa Fe, NM, 1999.

[9] T. Hermann, "Taxonomy and definitions for sonification and auditory display," in *Proceedings of the 14th International Conference on Auditory Display (ICAD2008)*, Paris, France, 2008.

[10] T. Ziemer, D. Black, and H. Schultheis, "Psychoacoustic sonification design for navigation in surgical interventions," *Proceedings of Meetings on Acoustics*, vol. 30, no. 1, p. 050005, 2017. [Online]. Available: https://asa.scitation.org/doi/abs/10.1121/2.0000557

[11] S. Matinfar, T. Hermann, M. Seibold, P. Fürnstahl, M. Farshad, and N. Nassir, "Sonification for process monitoring in highly sensitive surgical tasks," in *Proceedings of the Nordic Sound and Music Computing Conference 2019 (Nordic SMC 2019)*. Stockholm, Sweden: KTH: In Press, 2019.

[12] W. T. Fitch and G. Kramer, "Sonifying the body electric: Superiority of an auditory over a visual display

in a complex, multivariate system," in *Santa Fe Institute, Studies In the Sciences Of Complexity Proceedings*, G. Kramer, Ed., vol. 18. Reading, MA, USA: Addison-Wesley Publishing Co., 1994, pp. 307–326.

[13] T. Hildebrandt, "Towards enhancing business process monitoring with sonification," in *Business Process Management Workshops (BPM 2013)*, N. Lohmann, M. Song, and P. Wohed, Eds. Beijing, China: Springer International Publishing, 2014, pp. 529–536.

[14] T. Hildebrandt and S. Rinderle-Ma, "Toward a sonification concept for business process monitoring," in *19th International Conference on Auditory Display (ICAD 2013)*. Lodz, Poland: Lodz University of Technology Press, 2013, p. 323–330.

[15] M. Poret, S. Ibarboure, M. Robine, E. Duc, N. Couture, M. Desainte-Catherine, and C. Semal, "Sonification for 3d printing process monitoring," in *Proceedings of the 2021 International Computer Music Conference (ICMC 2021)*, Santiago, Chile, 2021.

[16] M. Gilfix and A. L. Couch, "Peep (the network auralizer): Monitoring your network with sound," in *Proceedings of the 14th USENIX Conference on System Administration (LISA'00)*. Berkeley, CA, USA: USENIX Association, 2000, pp. 109–118.

[17] M. H. Hansen and B. Rubin, "Babble online: Applying statistics and design to sonify the internet," in *Proceedings of the 7th International Conference on Auditory Display (ICAD2001)*. Helsinki University of Technology, Espoo, Finland: International Community on Auditory Display, 2001, pp. 10–15.

[18] C. Chafe and R. Leistikow, "Levels of temporal resolution in sonification of network performance," in *Proceedings of the 7th International Conference on Auditory Display (ICAD2001)*. Helsinki University of Technology, Espoo, Finland: International Community on Auditory Display, 2001, pp. 50–55.

[19] M. Barra, T. Cillo, A. De Santis, U. F. Petrillo, A. Negro, and V. Scarano, "Multimodal monitoring of web servers," *IEEE MultiMedia*, vol. 9, no. 3, pp. 32–41, 2002.

[20] E. Childs, "The sonification of numerical fluid flow simulations," in *Proceedings of the 7th International Conference on Auditory Display (ICAD 2001)*, Helsinki University of Technology, Espoo, Finland, 2001.

[21] Q. T. Tran and E. D. Mynatt, "Music monitor: Ambient musical data for the home," in *Proceedings of the IFIP WG 9.3 International Conference on Home Oriented Informatic and Telematics (HOIT 2000)*, A. Sloan and F. van Rijn, Eds., vol. 173. Kluwer, 2000, pp. 85–92.

[22] G. M. Vallejo Rosas, "Listenin: Ambient auditory awareness at remote places," Ph.D. dissertation, Massachusetts Institute of Technology, 2003.

[23] R. D. Patterson, T. F. Mayfield, D. E. Broadbent, A. D. Baddeley, and J. Reason, "Auditory warning sounds in the work environment," *Philosophical Transactions of the Royal Society of London. B, Biological Sciences*, vol. 327, no. 1241, pp. 485–492, 1990.

[24] H. Lazarus and H. Höge, "Industrial safety: Acoustic signals for danger situations in factories," *Applied Ergonomics*, vol. 17, no. 1, pp. 41–46, 1986.

[25] Z. Pousman and J. Stasko, "A taxonomy of ambient information systems: Four patterns of design," in *Proceedings of the Working Conference on Advanced Visual Interfaces (AVI06)*. Association for Computing Machinery, 2006, pp. 67–74.

[26] S. W. Williams, F. Martina, A. C. Addison, J. Ding, G. Pardal, and P. Colegrove, "Wire + arc additive manufacturing," *Materials Science and Technology*, vol. 32, no. 7, pp. 641–647, 2016. [Online]. Available: https://doi.org/10.1179/1743284715Y.0000000073

[27] A. Olwal, C. Lindfors, J. Gustafsson, T. Kjellberg, and L. Mattson, "Astor: An autostereoscopic optical see-through augmented reality system," in *Proceedings of International Symposium on Mixed and Augmented Reality*, 2005.

[28] A. Ceruti, A. Liverani, and T. Bombardi, "Augmented vision and interactive monitoring in 3d printing process," in *International Journal on Interactive Design and Manufacturing*, 2017.

[29] J. Wang, J. Erkoyuncu, and R. Roy, "A conceptual design for smell based augmented reality: Case study in maintenance diagnosis," *Procedia CIRP*, vol. 78, pp. 109–114, 2018, 6th CIRP Global Web Conference – Envisaging the future manufacturing, design, technologies and systems in innovation era (CIRPe 2018). [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2212827118312472

[30] A. Hattab and G. Taubin, "Rough carving of 3d models with spatial augmented reality," in *Proceedings of the ACM Symposium on Computational Fabrication*. ACM, Jun. 2019. [Online]. Available: https://doi.org/10.1145/3328939.3328998

[31] M. Weiser and J. S. Brown, "The coming age of calm technology," 1996.

[32] C. Wisneski, H. Ishii, A. Dahley, M. Gorbet, S. Brave, B. Ullmer, and P. Yarin, "Ambient displays: Turning architectural space into an interface between people and digital information," in *International Workshop on Cooperative Buildings (CoBuild'98)*. Darmstadt, Germany: Springer, 1998, pp. 22–32.

[33] D. S. McCrickard, C. M. Chewar, J. P. Somervell, and A. Ndiwalana, "A model for notification systems evaluation—assessing user goals for multitasking activity," *ACM Transactions on Computer-Human Interaction (TOCHI)*, vol. 10, no. 4, pp. 312–338, 2003.

[34] T. Matthews, A. K. Dey, J. Mankoff, S. Carter, and T. Rattenbury, "A toolkit for managing user attention in peripheral displays," in *Proceedings of the 17th annual ACM Symposium on User Interface Software and Technology (UIST04)*, Santa Fe, NM, USA, 2004, pp. 247–256.

[35] N. Sawhney and C. Schmandt, "Nomadic radio: Speech and audio interaction for contextual messaging in nomadic environments," *ACM Transactions on Computer-Human Interaction (TOCHI)*, vol. 7, no. 3, pp. 353–383, 2000.

[36] S. E. Hudson and I. Smith, "Electronic mail previews using non-speech audio," in *Conference Companion on Human Factors in Computing Systems (CHI96)*, Vancouver, British Columbia, Canada, 1996, pp. 237–238.

[37] E. R. Pedersen and T. Sokoler, "Aroma: Abstract representation of presence supporting mutual awareness," in *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI97)*, ser. CHI '97. Atlanta, GA, USA: Association for Computing Machinery, 1997, pp. 51–58.

[38] E. D. Mynatt, M. Back, R. Want, M. Baer, and J. B. Ellis, "Designing audio aura," in *Proceedings of the SIGCHI conference on Human Factors in Computing Systems (CHI98)*, Los Angeles, CA, USA, 1998, pp. 566–573.

[39] F. Kilander and P. Lönnqvist, "A whisper in the woods - an ambient soundscape for peripheral awareness of remote processes," in *Proceedings of the 8th International Conference on Auditory Display (ICAD 2002)*, Kyoto, Japan, july 2002.

[40] N. Rönnberg, J. Lundberg, and J. Löwgren, "Sonifying the periphery: Supporting the formation of gestalt in air traffic control," in *Proceedings of The 5th Interactive Sonification Workshop (ISon-2016)*, CITEC, Bielefeld University, Germany, 2016, pp. 23–27.

[41] T. L. Bonebright and J. H. Flowers, "Evaluation of auditory display," in *The Sonification Handbook*, T. Hermann, A. Hunt, and J. G. Neuhoff, Eds. Logos Berlin, 2011, pp. 111–144.

[42] B. S. Mauney and B. N. Walker, "Creating functional and livable soundscapes for peripheral monitoring of dynamic data," in *Proceedings of the 10th International Conference on Auditory Display (ICAD 2004)*, Sydney, Australia, 2004.

[43] D. Hausen, A. Tabard, A. Thermann, K. Holzner, and A. Butz, "Evaluating peripheral interaction," Munich Germany, 02 2014, pp. 21–28.

[44] M. Daniel, "Shape-changing Cylindrical Displays: Application to Data Physicalization and Peripheral Interaction for Energy Demand-Side Management," Theses, Univ. Bordeaux, Nov. 2018. [Online]. Available: https://hal.archives-ouvertes.fr/tel-01972386

[45] R. Jung, "Ambience for auditory displays: Embedded musical instruments as peripheral audio cues," in *Proceedings of the International Conference on Auditory Display (ICAD 2008)*. Paris, France: International Community for Auditory Display, 2008.

[46] C. Ho and C. Spence, "Using peripersonal warning signals to orient a driver's gaze," *Human Factors*, vol. 51, no. 4, pp. 539–556, 2009, pMID: 19899363. [Online]. Available: https://doi.org/10.1177/0018720809341735

[47] T. Hildebrandt, T. Hermann, and S. Rinderle-Ma, "A sonification system for process monitoring as secondary task," in *2014 5th IEEE Conference on Cognitive Infocommunications (CogInfoCom 2014)*. Vietri sul Mare, Italy: IEEE, 2014, pp. 191–196.

[48] T. Hermann, T. Hildebrandt, P. Langeslag, and S. Rinderle-Ma, "Optimizing aesthetics and precision in sonification for peripheral process monitoring," in *Proceedings of the 21st International Conference for Auditory Display (ICAD 2015)*, Graz, Austria, 2015, pp. 317–318.

[49] T. Hildebrandt, T. Hermann, and S. Rinderle-Ma, "Continuous sonification enhances adequacy of interactions in peripheral process monitoring," *International Journal of Human-Computer Studies*, vol. 95, pp. 54–65, 2016.

[50] S. Smith, R. M. Pickett, and M. G. Williams, "Environments for exploring auditory representations of multidimensional data," in *Santa Fe Institute, Studies In the Sciences of Complexity Proceedings*, G. Kramer, Ed., vol. 18. Reading, MA, USA: Addison-Wesley Publishing Co., 1994, pp. 167–184.

[51] L. Demany, M. Erviti, and C. Semal, "Auditory attention is divisible: Segregated tone streams can be tracked simultaneously," *Journal of Experimental Psychology: Human Perception and Performance*, vol. 41, no. 2, p. 356, 2015.

[52] W. W. Gaver, "What in the world do we hear? an ecological approach to auditory event perception," *Ecological Psychology*, vol. 5, no. 1, pp. 1–29, 1993.

[53] A. J. Watkins and M. C. Dyson, "On the perceptual organisation of tone sequences and melodies," *Musical Structure and Cognition*, pp. 71–119, 1985.

[54] P. N. Juslin and P. Laukka, "Expression, perception, and induction of musical emotions: A review and a questionnaire study of everyday listening," *Journal of New Music Research*, vol. 33, no. 3, pp. 217–238, 2004.

[55] P. Vickers, "Sonification for process monitoring," in *The Sonification Handbook*, T. Hermann, A. Hunt, and J. G. Neuhoff, Eds. Logos Berlin, 2011, pp. 455–492.