Public-space sonifcation for pedestrian trajectory nudging

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Alessandro Corbetta, Toros Senan, Lex Wöstemeier, Bart Hengeveld

Abstract Increasing the effectiveness and pervasiveness of crowd management measures is an urgent societal need given the continuous urbanization and the persistent growth of large crowd events. Rendering our environments smart and capable of dynamically nudging the crowd flow would provide an effective solution. This holds especially when a massive deployment of field stewards is impossible or not preferred. Yet, this is an outstanding scientific and technological challenge. Here, we present a proof-of-concept towards the usage of acoustic feedback as a way to smarten our environments and automate pedestrian guidance. We established a living lab experiment in a building at TU/Eindhoven (NL). For about 12 weeks, we tracked pedestrians in real-time and reproduced sounds (piano chords, in a wave field synthesis system) coherent with the pedestrian trajectories. We aimed at having pedestrians detouring to a path different from the "typical" for the area. We compare the effect of the acoustic feedback with the control condition (no sound, in random alternation with the feedback). After a transient "learning" phase, pedestrians appear to unexpectedly act contrarily to the feedback design, and rather detoured in opposite direction. This work substantially extends the analysis previously presented by the same authors in [1].

1 Introduction

Increasing the effectiveness and pervasiveness of crowd management measures is an urgent societal need given the continuous urbanization and the persistent growth

Alessandro Corbetta
Eindhoven University of Technology, Department of Applied Physics and Education Science e-mail: a.corbetta@tue.nl

Toros Senan
Eindhoven University of Technology

Lex Wöstemeier
Eindhoven University of Technology

Bart Hengeveld
Eindhoven University of Technology

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of large events [2]. Rendering our environments smart and capable of dynamically nudging the crowd flow would provide an effective solution. This could enable just-in-time routing and wayfinding, for the benefit of individual efficiency, comfort and safety. Trained field stewards are the current solution for pervasive management, yet large-scale steward deployments are prohibitive and not always possible (e.g. for event rapidly developing).

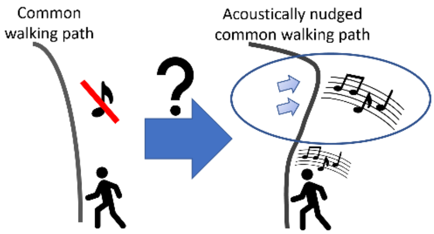

Fig. 1: Can just-in-time auditory feedback, triggered along pedestrian trajectories, alter the walking behavior? Can we nudge pedestrian dynamics so to transform the most common pedestrian trajectories observed in a facility to other, preferred, ones?

Establishing environments, seamlessly nudging crowds, requires a deep understanding of the outstanding physics and psychological aspects of crowd dynamics; a matter of intense multidisciplinary research [3, 4]. Similarly, the development of smart environmental nudges steering the crowd behavior is at its very infancy with only few studies [5, 6], based on visual stimuli. However, people are often visually occupied and thus less responsive to visual stimuli. Auditory feedbacks, still unexplored in the case of crowds, could enable intuitive, possibly subtle, custom information delivery.

This chapter presents the result of a 12-week long naturalistic experimental campaign aimed at investigating the effectiveness of tailored auditory feedbacks to nudge individual pedestrians from their typical trajectories. This is the first step towards steering the crowd behavior. Our core research question is: *can typical walking paths be altered by just-in-time auditory feedback?* (see conceptual sketch in Fig. 1).

We established a multichannel audio system for spatial sound synthesis. This system could play pedestrian position-dependent piano chords. Yet, only walking a path relatively far from the “typical walking path” allowed pedestrians to hear a complete 4-chords scale ascending in pitch. On the opposite, along “typical walking paths” an incomplete scale was audible. The sound generation process is based on real-time high-accuracy pedestrian tracking information driving a Wave Field Synthesis sound system.

We report on how this mechanism modifies, indeed reinforces, the choice of the walking path. We observe that after a relatively short period in which pedestrians alter their walking path and thus listen to the entire chord scale, they more strongly than in the control condition opt for path in which fewer sounds are audible. This contribution substantially extends our preliminary work [1] considering a longer experimental campaign and effects such as learning.

This chapter is structured as follows: in Sect. 2, we provide background on sonification. Besides, we introduce the sound delivery approach at the core of our sound nudges: wave field synthesis. In Sect. 3, we describe our experimental design and measurement facility. In Sect. 4, we present the results of our experimental campaign. A discussion section closes the chapter.

2 Sonification

The human hearing system is precise in encoding timing of sound events [7], able to process multiple sounds simultaneously [8], and efficient in sound localization [9]. This makes us fully aware of our acoustic environment. Exploiting this capacity is at the basis of sonification as a vehicle for human-computer interaction [10]. Auditory guidance systems are typically designed as single-user-single-feedback systems: a single user receives auditory feedback based on their actions concerning a target destination/movement [11]. Conversely, automating crowd management presents a different interaction requirement: the target point or destination is unknown, and the desired trajectory varies based on the crowd density, crowd speed, and positions of the pedestrians. Therefore, an efficient pedestrian steering system should use crowd behavior data, provide feedback to multiple users simultaneously, and vary intensity based on individual involvement.

Wave Field Synthesis (WFS). The sound stimuli employed in our experiment are delivered using Wave Field Synthesis (WFS) via a linear array of 16 loudspeakers. WFS is a spatial sound field reproduction technique that constructs a virtual auditory scene employing a large number of loudspeakers in a given listening space [12]. WFS has the advantage of delivering accurate localization of virtual sound sources [13] at predetermined points, lines (in our experiment) or planes. Employing WFS allows the generation of different sounds for different pedestrians (impossible with traditional spatial sound [14]).

3 Experimental setup

We established an indoor naturalistic experimental setup within a hallway in the Cascade building at Eindhoven University of Technology, The Netherlands (see Figure 2). This area connects laboratories and offices and is typically traversed by few hundred people per day, including students, scientific and technical staff which we track in real-time (details in the second part of this section). We performed our measurements during twelve weeks in the period 15th of November 2021–28th of February 2022. Due to the Covid-19 pandemic, partial lockdown measures had been in place in The Netherlands. This caused an unavoidable reduction in pedestrian measured (cf. Fig. 3(a)). The observation area has a rectangular shape of $4.7m \times 3.8m$. Pedestrians can traverse the hallway aiming at different destinations (cf. Fig. 2(a) regions A–E). Most frequently pedestrian walk from E to B (henceforth referred to as South-North) and vice versa (North-South).

We designed a grid-based interactive sonification system that generates sound stimuli to alter the typical walking trajectories, with focus on the South-North case.

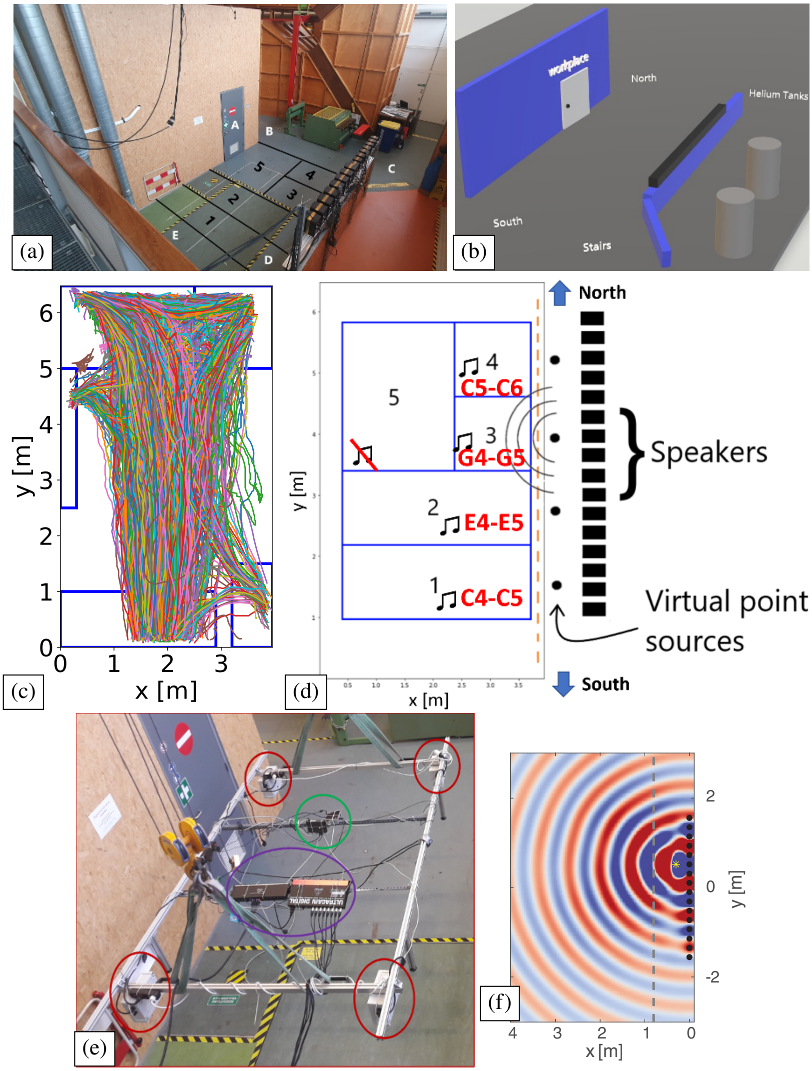

Fig. 2: Experimental setup: location, trajectories, sound synthesis system and tracking system. We monitor a passage area within the Cascade building at TU/Eindhoven (a, photo; b, 3D sketch). Pedestrians walking within zones 1–5 are tracked in real-time. Examples of trajectories acquired are in (c). Wave Field Synthesis sound stimuli are generated through the array of 16 loudspeakers on the right. Specifically, pedestrians in zone 1–4 hear chords as reported in (d), whereas in zone 5 no sound is played. We consider individual pedestrians walking from South to North (direction E-B in (a)) and vice versa (direction B-E in (a)). In panel (e) we report the overhead infrastructure that holds the depth tracking sensors (red circle), and sound generation devices (green, purple). (f) Wave fields of monochromatic focused sources, $f = 500$ Hz, reproduced by a linear distribution of 16 loudspeakers ($\Delta x = 20.75cm$) in 2.5D WFS. The black circles, the yellow asterisk symbols, and the dashed lines represent loudspeaker positions, virtual sound source positions, and the reference line, respectively. The colors show the sound pressure levels (red: highest, blue: lowest).

The experimental area is divided into five invisible sound zones, denoted as 1–5 in Fig. 2(d). When a pedestrian is tracked within sound zones 1–4, a pre-recorded short sound sample is played back. Conversely, no sound is played in zone 5. The sound samples are one and a half seconds-long piano sounds. Each consists of a *unison interval* (two notes an octave apart). The chords assigned to the zones 1–4 are, respectively, C4-C5, E4-E5, G4-G5, C5-C6. In this order, these ascend in pitch.

The typical South-North trajectories keep the left-hand side (in the reference of Fig. 2(a,d)) and thus cross regions 1-2-5. With such a trajectory, our sonification scheme produces only two chords. To hear the full sequence of four piano chords a pedestrian has to alter the typical trajectory and cross zones 1-to-4 (i.e. opt for 3–4 instead of 5), walking more on the right than usual. We activate our sonification system with a semi-random schedule, alternating experiment days (sonification on, 2+/week) control days (sonification off, 2+/week, see Fig. 3(b)). This aims at encompassing potential seasonal effects.

Our analysis, reported in Sect. 4, hinges on the average transversal position (x coordinate cf. Fig. 2(c,d)) that pedestrians keep amid the corridor ($L < y < H$, $L = 3$ m, $H = 5$ m). For each trajectory, e.g. the i-th one, we consider the observable $\hat{x}^i_{L,H}$

$$\hat{x}^i_{L,H} = E[x^i | L < y^i < H], \tag{1}$$

where E is the conditioned average and x^i, y^i are the coordinates of the i-th pedestrian trajectory. We shall consider only occurrences of pedestrians walking alone in the facility to avoid for the moment, interacting cases. We retain measurements for the South-North case (our main target), but also for the reversed case. This gives rises to four scenarios: South-North/Experiment, South-North/Control, North-South/Experiment, North-South/Control. For each of these we ensemble-average $\hat{x}^i_{L,H}$ over all the trajectories:

$$\hat{x}_{L,H} = \text{mean}_{i \in \text{trajectories}} [\hat{x}^i_{L,H}]. \tag{2}$$

Similarly, we retain the ensemble standard deviation as a measure of the typical fluctuation around the average.

Pedestrian tracking. The core component of the system, driving the audio generation and data collection, is a highly accurate real-time pedestrian tracking system. The system hinges on a grid of four overhead depth sensors, that enable privacy respectful and accurate tracking (cf. other works by one of the authors [5, 15, 16], by others [17] and state-of-the-art tracking performance [18]). We specifically employ the HA-HOG machine-learning based localization algorithm [19]. We use Orbbec Persee depth sensors arranged in a 2 x 2 grid and operating at 15Hz and produce a merged depth signal.

Wave Field Synthesis sound engine. The sound engine receives pedestrian position information from the tracking system and triggers short sound samples. There are four different sound samples, one for each sound zone, and each sound is placed at a virtual position with WFS. A linear array of 16-loudspeakers with an inter-distance of $\Delta x = 20.75$ cm between them are installed at the height of 175 cm on one side of the

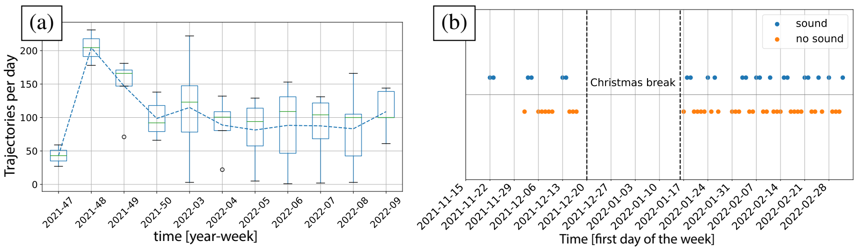

Fig. 3: Typical crowd dynamics in our experimental location during the measurement period. (a) Observed trajectories per day vs. the week. The boxplot reports the statistics of the week including median, percentiles and max/min. (b) Alternation of experiment and control days.

experimental area (Fig. 2(f)). The WFS operator is configured as a 2.5-dimensional WFS, which allows accurate localizations at any point on our reference line parallel and 80 cm away from the loudspeaker array. The sound samples are positioned in the area between the loudspeakers and the reference line.

4 Results

We report in Figure 4(a,b) the $\hat{x}_{L,H}$ statistics comparing experiment and control days and considering both South-North and North-South cases. We observe that in case South-North, the acoustic feedback has an effect, contrarily to the North-South case. Yet, at variance with our expectations, the average transversal position $\hat{x}_{L,H}$ shifts leftwards. This means that people opt to visit zone 5 (no sound) more likely than in the control case.

Considering the South-North case only, in Figure 4(c), we further condition on the measurement week. We report the relative nudging effect

$$\Delta = \frac{\hat{x}_{L,H}^{\text{experiment}} - \hat{x}_{L,H}^{\text{control}}}{\hat{x}_{L,H}^{\text{experiment}}}. \tag{3}$$

This indicator is positive in case the experimental condition manages to nudge the pedestrians to the right side (where the complete scale is audible) and negative if, on the contrary, in the control case people would walk more on the right side. We observe that the indicator is positive only in the first two weeks of the experiment. Thereby thus the nudge operated as expected. Later on the nudge had rather a repulsive effect with pedestrians opting to keep the left side.

5 Discussion

In this chapter we presented a first step towards the usage of auditory feedback as a way to nudge pedestrian walking trajectories. We designed our feedback to yield mildly detouring walking paths and tested it within a 12-week long naturalistic experiment. Our system coupled real-time anonymous tracking with a wave field

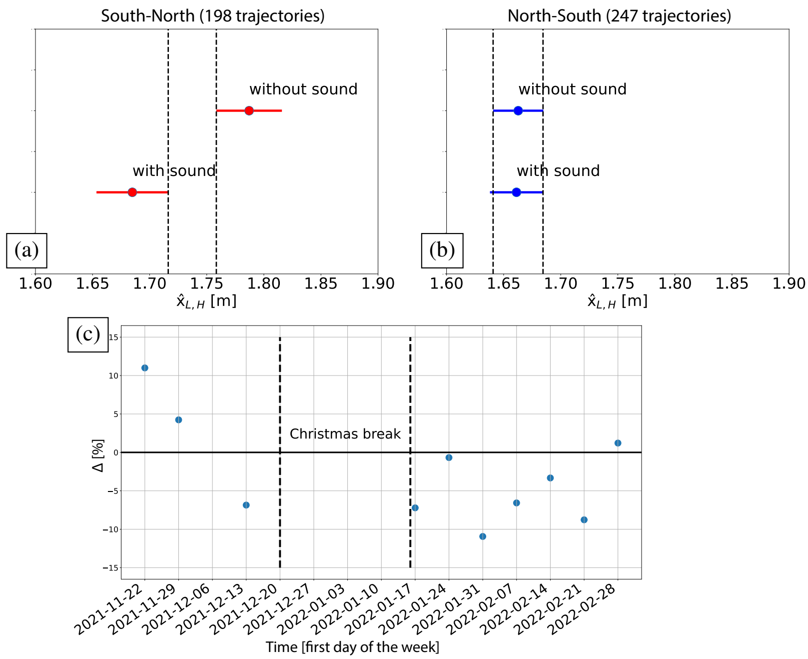

Fig. 4: (a-b) Average transversal pedestrian position amid the corridor $\hat{x}_{L,R}$ (solid dots) and related ensemble standard deviation (horizontal bars, twice ensemble standard deviation). (a) Case of South-North trajectories; (b) Case of North-South trajectories. In the South-North case we have a measurable nudging effect in comparison with the control condition. Pedestrians, however, shift further left and avoid hearing the complete four chords scale. In the North-South case no difference in behavior is visible. (c) Relative difference Δ (Eq. 3) in average transversal position between experiment and control measurements on a weekly basis. Only at the beginning of the experiment the acoustic feedback nudged people to opt for a rightwards path (our target), afterwards the opposite effect held, but in the final week.

synthesis sound generation. Our nudging hinged on providing a complete piano scale of ascending pitch only when pedestrians walked a mild detour (not signaled otherwise). In case of a common trajectory only a partial scale would be audible.

After an initial "transient period" of about two weeks in which our nudge managed the targeted detouring effect, we could almost exclusively observe the opposite reaction. People would opt to deviate from the common path but to get away from the fully sonified region. Indeed, we expect most of the pedestrian that traverse the area to be returning individuals that thus learned about the presence of the nudge and how to avoid it. It is also worth mentioning that our experiment has been held during a partial COVID-19 lockdown period ($2-4\times$ reduction of daily trajectories). We still regard this as positive result: our sonfication strategy managed to nudge the pedestrian paths, yet differently from our design expectation. We remark that we purposely established an advanced sonification system with multiple speakers, likely unfeasible in reality, but which gave us ample experimental freedom and that will be the core of forthcoming tests multi pedestrian tests.

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