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Sound signals to improve evacuation in road tunnels

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ABSTRACT

Although visual signage is the most common means of evacuation support in road tunnel emergencies, these can be of little help when there is dense smoke product of a fire. In such cases, auditory messages can lead evacuees out of a tunnel even in conditions with limited vision. This paper presents the results of two full-scale experimental studies designed to evaluate whether sound signals can help people to evacuate out of a smoke-filled tunnel due to a fire. Experiment 1 tested two sound signals (i.e. clicking sound and whistling sound) and their effect in aiding evacuation from a tunnel with poor vision. Experiment 2 was based on the results from Experiment 1 and tested two sound signals (i.e. clicking sound and bell sound). Experiment 2 confirmed that the evacuation success rate increased as people received information that they should follow the sound. In addition, subjective assessments by the participants revealed a higher preference for the tone-based sounds (i.e. bell sound and whistling sound) over the clicking sound. The results of this study can have implications in the assessment of new measures to support a more efficient evacuation from tunnels during emergencies.

1. Introduction

Past emergency experiences in road tunnels have revealed the importance of establishing satisfactory evacuation systems that effectively guide people out of a critical situation. For instance, the current Norwegian norms are clear regarding visual exit signage that need to be present in road tunnels. Dimensions, colour, font selection, and font size are regulated and are broadly used across the Norwegian roads and road tunnels [1,2].

Although many governmental manuals and reports across the world have well-established guidelines for visual exit and evacuation signage, visual aids are of little assistance when visibility is poor. Several factors can hinder the visibility of such visual signage in road tunnels: unfamiliarity with the physical environment, reduction of visibility due to smoke, people with impaired vision, etc. Moreover, behavioural research indicates that human factors also play a role in evacuation procedures. Studies have indicated that people tend to evacuate a building via the same route they used when they entered the premises [3], and this could lead to people walking past near emergency exits [4].

As a solution for improving evacuation procedures, acoustic signals have been proposed and studied for some years [5–9]. In particular, directional sound technology has been tested as a means to aid people to locate an emergency exit by identifying the source of the sound [4,5,10]. These studies conclude that audio signals constitute valuable evacuation means, and that their application is crucial [11].

An advantage of audio signals is the universal comprehensibility of abstract sounds. If speech messages were to be deployed, an obvious challenge is the language used for such messages. Since most road tunnels are public and road users can be of different nationalities, a language barrier is evident, putting in detriment the people that cannot understand the evacuation messages. In that regard, audio signals using sound instead of speech constitute a valid alternative. Yet, since people are inclined to seek for visual cues to find emergency exits, it is unknown to which extent they would understand that they are supposed to follow the sound.

Several studies have pointed out that audio signals are not only effective, but that the addition of audio instructions greatly improved evacuation procedures [12]. For example, Burns et al. [11] indicated that three quarters of their study participants made the decision to evacuate only after audio instructions were provided. Van Wijngaarden, Bronkhorst, and Boer [13] revealed that in an experiment which simulated a ship's interior, only 38% of the participants could evacuate using

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just their intuition, whereas 88% of the participants evacuated successfully when a chime followed by an explicit spoken instruction (i.e. "*exit here*") was used. Although the use of sound beacons above emergency exits can be effective, the challenge is that many Norwegian road tunnels do not have emergency exits. This means that such systems will not work and that people must be guided out of the tunnel. Studies about guiding persons in tunnels following certain directions have also been carried out. For instance, Van Wijngaarden, Bronkhorst [13] tested a sound system using the precedence effect to give the impression of an evacuation signal coming from one direction. They concluded that this method was more effective than using frequency modulation as code for indicating direction, but also stated that it is only effective around specific locations. The frequency modulation technique is stated to require training of the evacuees to work sufficiently, something that is undesirable for an evacuation system [13].

Moreover, the efficacy of sound signals is dependent on the type of sound that is used. One study suggests that complex tones with distinctive timbre and pitch are recognizable as an evacuation signal, and are easier to distinguish amidst background noise [14]. An earlier study [15] suggests a class of sounds with strong repulsive response, which could potentially be exploited for directing people away from the source of danger. Several such sounds were generated, but ultimately never used in live trials due to ethical concerns.

While visual exit signages have been well-researched, a lot remains unexplored for audio signals. Although a number of studies have been performed to elucidate the effect of acoustical guidance during evacuation, there remains a need to further test different techniques. This knowledge gap can hamper the implementation of acoustic measures for evacuation purposes, thereby potentially worsening the evacuation efficacy. It is well known that rapid evacuation during critical emergency situations may reduce the number of injured and save lives. The goal of the present study was to evaluate whether two different acoustical techniques can help people to evacuate out of a smoke-filled tunnel (e.g. as a result of a fire). To this end, the study was designed to answer the following research questions:

RQ_1: Is evacuation from a smoke-filled tunnel easier when audio signals are used?

RQ_2: How do speech messages support audio signals during tunnel evacuation?

The following sections describe the method used and the results of the study.

2. Method

Two full-scale experiments were designed to assess the success rate of sound signals for leading evacuees out of a road tunnel. The first experiment was performed in the tunnel of Ladehammer wastewater and sewage treatment plant in Trondheim, and the second in the Runehamar test tunnel in Åndalsnes, both in Norway.

Both experimental studies were subject to an application to the Norwegian Social Science Data Services (NSD – *Norsk Samfunnsvitenskapelig Datatjeneste*), considering that personal information was collected (e.g. age and gender). The NSD granted the approval to perform the studies.

The following subsections describe the setting and selection of the stimuli for both experimental studies.

2.1. Experiment 1: Ladehammer tunnel

The aim of Experiment 1 was to investigate whether sound signals can lead people out of a tunnel with poor vision, product of smoke due to a fire. The experimental hypothesis for Experiment 1 was:

H1. Sound signals work to guide evacuating persons in a certain direction in a smoke-filled tunnel.

2.1.1. Stimuli

The experimental sessions occurred at the entrance tunnel located at Ladehammer wastewater and sewage treatment plant in Trondheim. This tunnel is 75 m long and 6.5 m wide and leads to a larger mountain hall. The road is made of concrete and the roof and walls are covered with spray concrete. The surfaces of the walls were rough and irregular. The established experimental area was of approximately 80 m. Fig. 1 shows a sketch of the test setup in the tunnel. At one end of the tunnel was the main gate that led out of the mountain, whereas the other end directed into a large mountain hall.

The experimental sessions were carried out during one week in early February 2020. The following subsections describe the setting and selection of the stimuli for the experimental design.

a Audio nodes: Five sound nodes were mounted on signposts, 2.7 m above the ground, and approximately 0.30 m from the tunnel walls. The audio nodes were placed inwards in the tunnel with 20 m intervals. The interval distance was decided based on the number of prototypes available (five) and the length of the tunnel.

b Fan noise: In road traffic tunnels there are fans used to ventilate out exhaust gas and smoke during fires. These fans make noise that can affect the ability to perceive sound signals. Since there were no fans in the test tunnel, fan noise was simulated using one speaker in each end of the test section. Recordings from the fire fans in the *Oslofjord* tunnel (recorded in June 2019) were played by iPods connected to active PA speakers (JBL 515XT). The speakers were placed on the ground rather than in the ceiling due to health and safety concerns. During tunnel fires, fans are not running the first minutes after a fire has been detected, to reduce the amount of oxygen supplied to the fire.

c Sound signals: The sound signals used in the experiments were selected after representatives from Norphonic and SINTEF evaluated different signals. Two different sound methods were used to create guiding sound signals. The first signal was click-based (called clicking sound) and consisted of a footstep sound played on single speakers with a 500 ms time delay. The sound progressed from speaker to speaker along the tunnel to guide evacuating persons in the desired direction. The second method created a tone-based sound (called whistling sound) and used a simulated Doppler effect to give the impression of a sound source moving through the tunnel. A self-produced Doppler effect sound created by Norphonic was used based on Jung, Kim, & Chung [6]. See Appendix A for details about the sounds used.

The experimental setting is shown in Figs. 1 and 2.

2.1.2. Data collection: objective and subjective tests

To test the experimental hypothesis, the success criterion for evaluating the efficacy of the sound signals was defined as whether the participants walked in the desired direction, i.e. following the sound. In addition, subjective evaluations of the sound signals were performed by the participants via questionnaires after completing the experiment. This post-test questionnaire included 12 questions, both multiple-choice, 5-point Likert-typed, and open-ended.

The questionnaire aimed to gather information regarding the participants' general experience of the test, their chosen sound signal ("*What was that which helped you to get out of the tunnel?*"), their subjective evaluation of the sound signals in general ("*Was the sound helpful? if so, how would you characterize the sound that helped you to get out of the tunnel?*"), and their preferred sound signal (i.e. clicking sound and whistling sound).

Furthermore, three 5-point Likert-typed scale questions were used to evaluate the perceived clarity, comprehensibility, and comfort of the sound signals. These three items are described in Table 1.

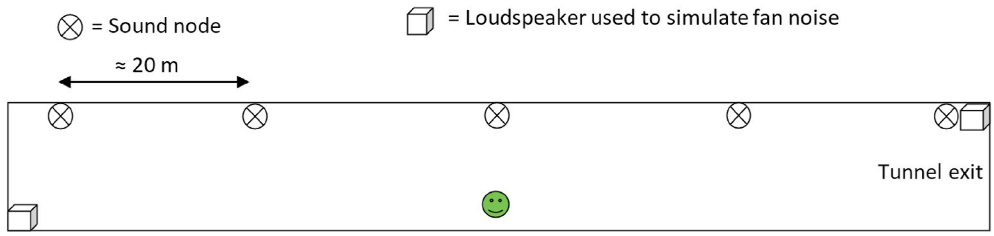

Fig. 1. Experimental setting depicting location of the sound nodes, speakers for the fan noise, and start position of the participants for Experiment 1.

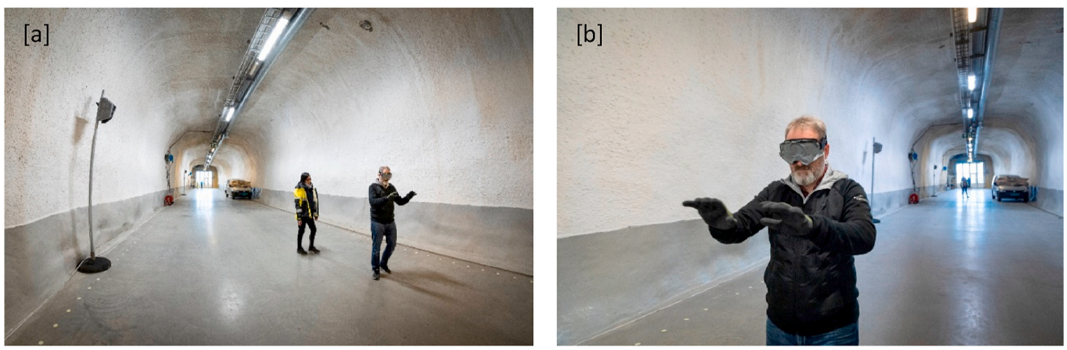

Fig. 2. Interior of the Ladehammer tunnel in which Experiment 1 took place [a], and participant using covered slalom skiing goggles to simulate poor vision in the tunnel [b]. Photos: Thor Nielsen, SINTEF.

Table 1
Questionnaire items for comparison between the two sound signals.

Questionnaire item	Question	Scale Range
Perceived clarity	How clear could you hear the sound signals?	1 - Could not hear it at all 5 - Could hear it very clear
Comprehensibility	How easy was to comprehend that the sound signal could lead you towards a specific direction?	1 - Difficult 5 - Easy
Comfort	Were the sound signal level comfortable?	1 - Very uncomfortable 5 - Very comfortable

2.1.3. Participants

The participants were recruited via the experimenters' own network contacts, student and school parents' organizations, and social media. The participation was voluntary and was rewarded with either a movie ticket or a contribution of 100 NOK (around 10 euros) to their organization. The total sample size was of 30 participants (14 female, 16 male), between 18 and 63 years old ($M = 36.4$, $SD = 12.1$).

2.1.4. Experimental setting and procedure

For the user test, thirty participants took part in the experiment in individual sessions. The same protocol was maintained in each of the sessions. Upon arrival, participants were briefed on the experiment procedure (i.e. experimental protocol, duration, their rights as well as ethical aspects regarding data collection). After signing a consent form, they filled in a pre-test questionnaire focussed on demographical data and then proceeded to undertake the test.

Participants were instructed to evacuate the tunnel in the direction they deemed reasonable. Since the aim was to investigate if the guiding purpose of the sound signals was intuitive, no information about the signals was given. To simulate poor vision due to a smoke-filled tunnel, the test participants were blinded using ski goggles covered with duct tape. Participants started each test scenario inside a car parked in the tunnel. They were then led to the starting spot, in which they were spun a few times and eventually placed facing different cardinal positions (also randomised) to avoid any spatial reference in the tunnel (e.g. having a preconceived idea of where the tunnel exit was located). They were then instructed to start walking towards the exit. An assistant walked near them during the entire experimental session to prevent injuries. When it was clear that the participants were determined to follow a specific direction to evacuate, they were guided back to the parked car to perform the subjective evaluation and continue with the next scenario.

Five different scenarios were tested in each experimental session: one reference scenario without sound signal (but with low fan noise) and four scenarios with sound signals (two with high fan noise and two with low fan noise). The direction of the sound signals was randomised to prevent a learning effect from the participants (e.g., the participants choosing to go in the same direction as in a previous scenario). Table 2 shows an example of an experimental session presented to each participant. The scenarios with sound signals were randomised so that the order would not be the same for all participants.

The purpose of the reference scenario was to investigate systematic errors that may have occurred. Examples of systematic errors that can affect the result are fresh air coming from the exit, slope on the road in the tunnel, light leakage, surrounding noises from the treatment plant, etc. The scenarios with low fan noise simulated the first few minutes after a fire has been detected and where fans are not yet fully activated. Additionally, the low fan noise helped masking the noises from the treatment plants. The level of fan noise was then approximately 65 dBA. The scenarios with high fan noise simulated the situation where fans in a

Table 2
Experimental stimuli.

Test number	Fan noise	Sound signal
1 (reference)	Low	None
2	Low	Clicking sound
3	High	Clicking sound
4	Low	Whistling sound
5	High	Whistling sound

tunnel run in fire mode. Measurements of fire ventilation in the Oslofjord Tunnel showed that the levels reached up to 95 dBA. To prevent causing discomfort or hearing damage, the high fan noise was limited to 85 dB.

Upon completing all five scenarios, the participants were asked to fill out a post-test questionnaire. Most experimental sessions lasted just under 30 min, with some participants managing to complete the experiment considerably faster.

2.2. Experiment 2: Runehamar tunnel

Based on the results of Experiment 1 (see Section 3.1), the objective was to investigate whether the information received by the participants indicating to follow the sound influenced people to choose the right direction. The hypothesis of Experiment 2 was therefore:

H_2: Prior information indicating to follow the sound signals increases the number of people going in the right way.

The second experiment was carried out in a full-scale experiment in a real tunnel, i.e. Runehamar tunnel administrated by the Norwegian Public Roads Administration. Further description of tunnel characteristics are described in the subsequent section.

2.2.1. Stimuli

The experimental sessions occurred at the Runehamar tunnel, located about 5 km from Åndalsnes, Norway. The Runehamar tunnel is a two-way asphalted road tunnel, with ceiling and walls in rough blasted rock. It is approximately 1600 m long, 9 m wide and 6 m high. The tunnel was retired 20 years ago when a new parallel tunnel was built for road traffic and is now mostly used as test tunnel for e.g. fire research. The experimental area was set up 200 m inside the tunnel. The tunnel entrance was covered with a tarpaulin to prevent participants from seeing daylight while doing the tests, as shown in Fig. 3.

The experimental sessions were carried out during one week in August 2020. The following subsections describe the setting and selection of the stimuli for the experimental design.

Fig. 3. Entrance to the tunnel covered by a tarpaulin to avoid daylight coming in. Photo: Carl Södersten, SINTEF.

a. *Audio nodes:* The evacuation system consisted of the same audio nodes as the first experiment, but this time ten nodes were mounted on the wall with their own brackets, 2.7 m above the ground. The audio nodes were placed inwards in the tunnel at 25 m intervals. Since technical cabinets are located every 125 m in Norwegian tunnels, it is considered that 25 m will support a straightforward installation. The total length of the test section was therefore 225 m.
b. *Smoke machine:* During the test, smoke machines were used to increase the realism of the test. The machines were operated by a person from the local fire service in Åndalsnes. The density of the smoke varied due to drafts in the tunnel, and the visibility at the test area ranged from 1 to 20 m approximately. Despite these variations, the smoke was held thick enough so that participants faced a wall of smoke in both directions.
c. *Fan noise:* Since the fans in the tunnel could not be used during the testing due to the tarpaulin that covered one of the openings, the fan noise had to be simulated. This was done by using the same loudspeakers and sound files as in the first experiment. The fan noise was measured and assessed during the pilot test the day before the user test started. A sound level meter (EXTECH SL510) was used to adjust the sound level of the fan noise. The noise level was measured to be between 73 dBA and 77 dBA in the test area. This is lower than real fire fan noise, but as discussed earlier, for ethical and HSE reasons, noise levels must be kept at reasonable levels to prevent discomfort for the participants. The fan noise served to mask surrounding sounds and to increase the realism of the evacuation scenarios.
d. *Sound signals:* Two different sound signals were used to create a guiding sound effect: a clicking sound (the same as in Experiment 1) and a bell sound. The signals were played sequentially on speakers with a marked time delay of 1 s to mimic sound moving physically through the tunnel in the hope that it would guide evacuating people in the desired direction. The delay needed to be increased from Experiment 1 considering that the bell sound was 0.7 seconds long. The sound level of the lead sounds was assessed subjectively by Trafsys subcontractor, Norphonic. First, the bell sound was adjusted to be clearly audible over the background noise. Subsequently, the clicking sound was adjusted to feel as loud as the bell sound. A few people present on site were polled whether they felt the sound levels were comparable, until an agreement was reached. The signal-to-noise ratio was not measured. See Appendix A for details about the sounds used.

The experimental setting is shown in Fig. 4 and Fig. 5. At one end of the tunnel was the opening through which the participants entered. The first sound node was located 200 m into the tunnel.

2.2.2. Data collection: objective and subjective tests

The success criterion for evaluating the efficacy of the sound signals was similar to the Ladehamar experiment, i.e. whether participants decided to exit in the direction where the sound signals were leading. The outcome is summarised in Section 3.2.

In addition, participants filled in a questionnaire regarding their impressions of the sound signals. The questionnaire contained 20 questions, most of which 5-point Likert-type, but also multiple-choice questions and open-ended questions.

The questionnaire aimed to collect information regarding chosen direction ("*What helped you to choose direction?*"), sound level ("*Could you hear the sounds equally good on each test?*"), subjective evaluation of the sound signals ("*Were the sounds helpful? In that case, how would you describe the sounds that helped you to choose a direction?*"), and signal preference ("*Which sound worked best to help you choose a direction?*"). Sound signals were assessed with 5-point Likert-type scale questions (Table 3).

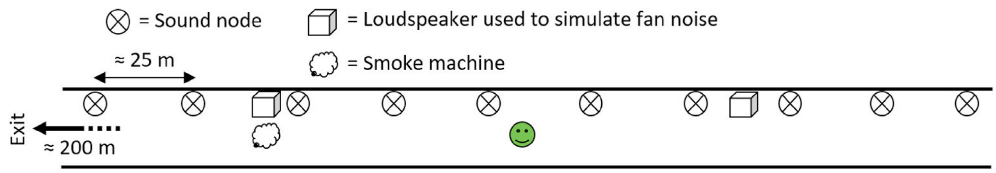

Fig. 4. Experimental setting depicting location of the sound nodes, speakers, smoking machine and start position of the participants for Experiment 2.

Fig. 5. Experimental setting depicting the Runehamar test tunnel used for Experiment 2 [a]; smoke machines filling up the tunnel [b]; gradual loss of vision product of the smoke [c]; and the perceptually limited vision in the tunnel to simulate evacuation conditions in a smoke-filled tunnel due to a fire [d]. Photos: Carl Södersten, SINTEF.

Table 3
Questionnaire items for comparison between the two sound signals.

Questionnaire item	Question	Scale Range
Evacuation message prior to the signals	How easy was to understand the evacuation message?	1 - Difficult to understand 5 - Easy to understand
Perceived clarity	How clear could you hear the [*x*] sound?	1 - Could not hear it at all 5 - Could hear it very clear
Comprehensibility	How easy was to comprehend that the [*x*] sound could lead you towards a specific direction?	1 - Difficult 5 - Easy
Comfort	Was the [*x*] sound level comfortable?	1 - Very uncomfortable 5 - Very comfortable

*Table note: [x] refers to the type of sound signal, i.e. either bell or clicking sound.

2.2.3. Participants

The participants were recruited via newspaper advertisements and via local sports club. Most participants lived near the city of Åndalsnes. The participation was voluntary and was rewarded with a single payment of 1000 NOK (around 100 euros). The sample size consisted of 33 participants (10 female, 23 male) aged between 23 and 78 years (M = 43, SD = 11.8). All participants were Norwegian, and only two reported having received evacuation training. Four participants (i.e. 12 % of the sample) declared having reduced hearing but none used any type of hearing aid.

2.2.4. Experimental setting and procedure

Similar to Experiment 1, the 33 participants took part in the experiment in individual sessions. Participants were picked up from a nearby parking lot outside the tunnel and driven to the test site, where the initial welcoming protocol was followed. After being briefed on the experiment (i.e. experimental protocol, approximate duration of the experiment, their rights and ethical considerations concerning the collection of data, task information and verbal instructions for the experiment) participants were required to sign a consent form.

Participants then filled in a pre-test questionnaire gathering demographical data (i.e. age, gender, education, kilometres driven last year, evacuation training, reduced hearing, perceived tiredness prior to the experiment). Next, participants were accompanied to a car parked inside the tunnel and then driven to the test location 250 m further down the tunnel. During the drive, participants were asked to cover their eyes to avoid spatial recognition of the tunnel. Because the experiments were undertaken during the Covid-19 pandemic, the original plan of using taped ski goggles (as in the Ladehamar experiment) was decided against to avoid participants sharing items. Once the participant reached the start position (see Fig. 5), the hypothetical scenario was presented verbally by the test administrator (in Norwegian) inside the car as follows:

> "You have reached about the middle of a long tunnel when the traffic suddenly stops. You do not know why the traffic stops, and smoke rapidly surrounds the car. You are not sure how far it is to the nearest exit or emergency exit. The following evacuation message is played on the DAB network".

The test administrator then played an evacuation message on a portable speaker in the car. Three scenarios were evaluated by the participants: one reference scenario without signal followed by one scenario for each signal (in randomised order).

The evacuation messages were different for the reference scenario and the sound signal scenarios and were played twice before each scenario (also in Norwegian).

- Reference scenario: *Fire in the tunnel. Evacuate immediately.*
- Sound signal scenarios: *Fire in the tunnel. Evacuate immediately. Follow the sound.*

The direction of the sound (and thereby hypothetical tunnel exit) was also randomised (to remove any bias related to the direction chosen by the participants) and was balanced so that it moved inwards and outwards with approximately the same distribution. After hearing the evacuation message, participants were asked to step outside the car, close the door, assess the situation, and then come back inside the car and indicate which direction they would have chosen. The procedure was then repeated for the following scenario.

Upon finishing the three scenarios, participants were driven back and escorted out of the tunnel and were asked to fill out a post-test questionnaire, inquiring about their impressions of the sound signals. The questionnaire is described in Section 2.2.2.

There was no time limit for the participants to decide which direction to take in each scenario, but participants often decided upon a direction within one or 2 min. Each experimental session, including transport in and out of the tunnel, lasted less than 30 min.

2.2.5. Statistical analysis

The statistical analysis was performed using the Statistics and Machine Learning Toolbox in Matlab [16].

It was assumed that the reference case, with no sound signal, had a random behaviour with 50% chance of evacuating in either direction. This was supported by the results from Experiment 1 where 17 went in one direction and 13 in the other. In Experiment 2, on the other hand, 26 went outwards (back the way they came in) and only 7 went inwards into the tunnel. This difference was significant (binomial test using z-test approximation, $z = 3.31, p < 0.001$) and must be taken into account when performing the statistical analysis on the sound signals. In Experiment 1 a binomial test using z-test approximation was used to compare the sound signal results with a 50% random choice, while in Experiment 2 a chi-squared test was used to compare the sound signal results with the observed reference.

A Fisher's exact test was used to compare the different sound signal cases, both in Experiment 1 and 2. In addition, a logistic regression was performed to see if any of the other variables (e.g. age, sex, hearing impairment, and direction of the sound) affected the results.

3. Results

3.1. Results experiment 1

The evaluation criterion for assessing the effectiveness of the sound signals was whether the participants indicated the correct way out of the tunnel, i.e. towards the direction of the sound. The fan noise level did not have any significant impact on the outcome. As seen in Fig. 6, distribution was identical for the clicking sound, while for the whistling sound a slightly larger proportion chose the correct direction when the fan noise was high, though this difference was not statistically significant (Fischer's exact test, $p = 0.41$). Eighteen of the participants stated that they could not hear the sound signal as well on each test, but this is not reflected in the results.

Since the fan noise level did not have any impact on the results, these tests were combined in the following analysis. The outcome per signal is summarised in Fig. 7 and shows that the participants in 42 out of 60 experiments went in the correct direction. This is significantly different from a random 50% distribution ($z = 2.582, p = 0.005$) and supports H_1.

In the post-test questionnaire, participants were asked if the sound helped them evacuate. Among those who answered positively (Fig. 8) the success rate was 75% (compared to 67% overall). The difference between the sound signals was not statistically significant (Fischer's exact test, $p = 0.81$).

A logistic regression analysis showed that none of the other variables had any significant effect on the results (not shown here).

3.2. Results experiment 2

Fig. 9 shows the results for each signal. 91% of participants chose the correct way with the bell sound and 85% with the clicking sound.

A chi-squared test confirms that this is statistically significant ($p < 0.001$) for both sounds (see Appendix B for details). These results also support the first hypothesis H_1.

In addition, statistical analyses were performed to test the second hypothesis H_2, which consider that providing a message indicating to

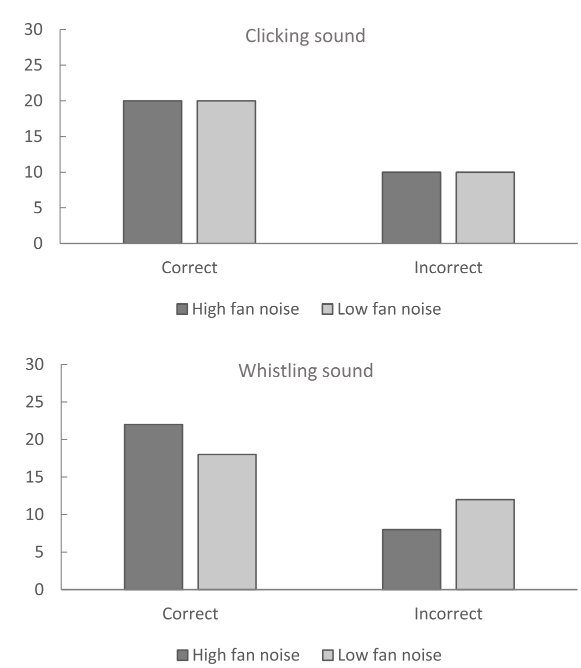

Fig. 6. Number of participants walking in the right and wrong direction distributed on type of sound signal and levels of fan noise.

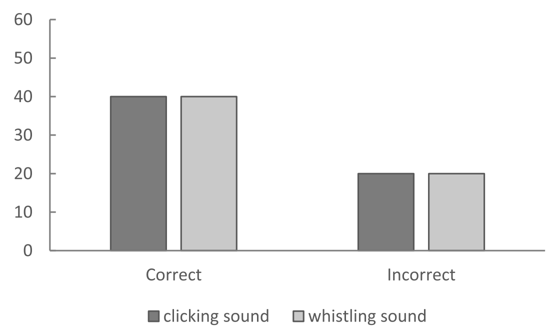

Fig. 7. Total number of participants who walked in the correct or incorrect direction with both sound signals.

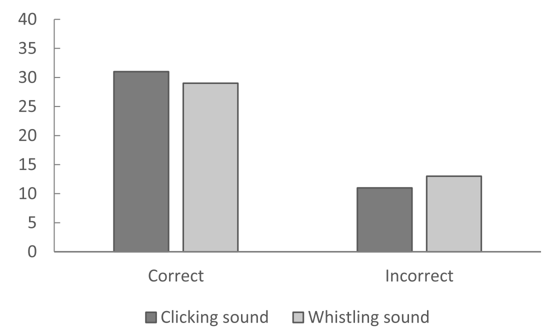

Fig. 8. Number of participants walking in the right and wrong direction and who declared that the sound signals helped to find their way out.

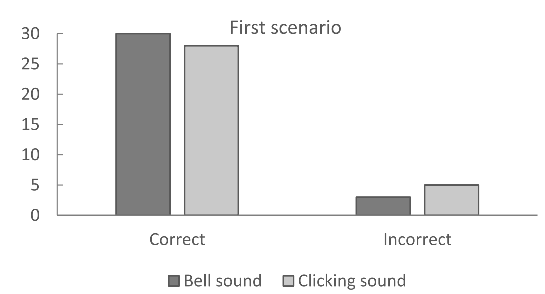

Fig. 9. Total number of participants that chose the correct or incorrect direction for the two sound signal scenarios.

follow the sound signals increases the number of participants going in the right way. The comparison is done using the click sound from both experiments. Forty out of 60 participants went in the right direction in Experiment 1, and 28 out of 33 went right in Experiment 2. Using a one-sided Fisher's exact test, we find that this is a significant difference ($p = 0.047$). This is used to answer hypothesis H_2 and suggests that prior information is important to increase the number of people going the right way.

Furthermore, the subjective responses gathered from the questionnaires revealed a slightly higher preference for the bell sound than for the clicking sound (see Fig. 10). Regarding clarity, the bell sound scored 4.5 and the clicking sound 4.1, while comprehensibility was rated 4.2 and 3.7 respectively. Comfort of the sound level was rated 4.5 and 4.1 respectively. The participants answering 3 or less on the comfort question were asked a follow-up question of the reason. For the clicking sound, six participants said the sound was too low/difficult to hear. Three participants said the same thing about the bell sound. No participant considered the sound from the nodes to be too high.

Participants were asked which sound they deemed most helpful. Twenty-one participants (64%) preferred the bell sound as opposed to only four (12%) preferring the clicking sound while eight participants (24%) had no preference. This difference is statistically significant different from a random distribution ($\chi^2 = 14.4, p < 0.001$).

4. Discussion

The results from both experiments support the hypotheses that sound signals can be used to guide evacuees in a specific direction in a tunnel. Despite that no explicit information regarding guiding sound was provided in Experiment 1, 67% of participants chose the correct direction. The proportion was higher (75%) among those who declared that their decision was based on the signals. Though this difference was not statistically significant, it suggested that the success rate could be increased by providing explicit information to follow the signal. This insight set the premises for the design of the second experiment.

Two different acoustical techniques were used to guide the evacuees in Experiment 1. The clicking sound was a recording of a footstep that was used to give the illusion of someone walking in one direction. This effect was created simply by playing one step on each sound node, with normal step frequency (approx. 120 steps/min, i.e. 500 ms between each step). Using this method, the sound physically moves from one sound node to the next.

The whistling sound simulated a doppler effect and sounded completely different from the clicking sound. Several of the participants preferred this sound since it was perceived as "alarm-like" and could be clearly heard. A challenge with the doppler sound was that it required accurate synchronisation of the loudspeakers, and the psychoacoustic effect could vanish if some nodes did not play its sound. The doppler sound was also initially constructed to work for segments of 50-70 meter, and even if it could be possible to create another sound for longer segments, it would require more experimental development and testing. Since this method did not outperform the clicking sound objectively, it was rejected for Experiment 2. Instead, a more audible sound (bell) was added to the first method to see if this was preferrable.

Although the test set-ups differed in several aspects, the statistical comparison between Experiment 1 and 2 indicates that providing prior specific instruction about following the sound does significantly increase the success rate. This supports the hypothesis from Experiment 2.

In Experiment 2 the participants were not blindfolded, they did not know how long the tunnel was, and for the reference case they were only told to exit the tunnel. Because of the smoke filling the tunnel and the tarpaulin covering the entrance, the participants could not sense in any way what could be the best way to exit. A possible explanation of why most went outwards (back the way they came in) is that it feels safer to go back the way you have entered. If there had been a car crash or a fire, it seems reasonable that one would think that this has happened in the part of the tunnel you have not driven through. This is also supported from other studies [3].

The results from the subjective evaluations from the participants in Experiment 2 shed a clearer light on the comparison results, with a larger number of participants preferring the bell sound over the clicking sound. Possible explanations over this preference could be found in the participants' comments. For instance, it was commented by a participant that the clicking sound could be confused with other sounds in the tunnel, so the use of a more distinct sound that differs from the surroundings seems to be wise. It is probably also possible to optimize this sound even more, either by adjusting the sound level, the frequency content, or the time delay between the sound nodes. Since about 90% of the participants went the right way, it is still not certain that the potential for improvement is particularly great, and thus this requires further research.

As pointed out previously, the fan noise level used during both experiments was lower than actual noise from fire ventilation. During

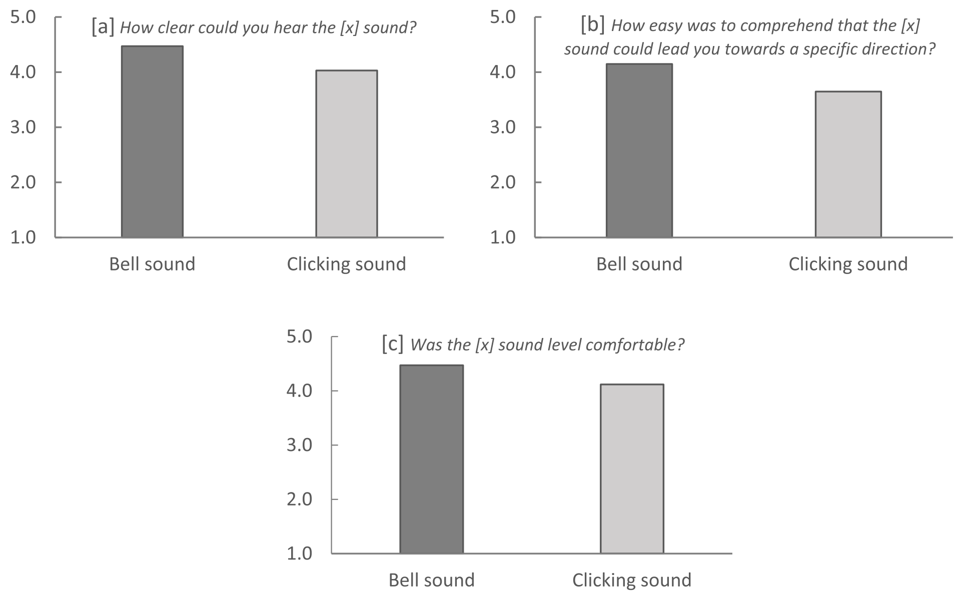

Fig. 10. Graphical plots for the comparison of the sound signals in the evaluation of perceived clarity [a], comprehensibility of sound signal [b], and comfort [c].

measurements made in the *Oslofjord* road tunnel during June 2019, the noise level from the real fire ventilation was measured to be up to 95 dBA. Due to the possible risk of hearing damage, it is not ethically justifiable to carry out user experiments with such a noise level, thus the use of lower noise levels in both experiments. A higher background noise level could influence the perception of the sound from the nodes, but this can be managed by increasing the sound level from the nodes. At very high sound levels the perception can, however, also be deteriorated by the mere fact that the sound is too loud and unpleasant. No participant considered that the sounds used in the experiments were too high, suggesting additional research efforts to investigate whether the sound level could be further increased.

Other sounds may also influence the evacuation sound in case of a real fire. Evacuees from the Gudvanga tunnel fire in 2013 explained that they could hear explosions (probably from the tires of the burning truck), cars crashing into other cars and walls, and people panicking [17]. All these sounds could also mask the evacuation sound, but in most cases, these are abrupt sounds that will only cause intermittent disturbance.

A limitation of the study is that the sound levels from the nodes were not measured, only subjectively assessed to be "clearly audible" and comparable in loudness. This means that there might have been differences in how well the sounds were perceived, and that this could have affected the results. Since some participants commented that the click-based sound was more difficult to hear, this could be the reason. However, this limitation does not diminish the relevance of the findings exposed in the present study, as the signal-to-noise ratio is especially important to understand speech messages, yet the sounds used in this study do not have the same requirements since they do not contain spoken information. Furthermore, the objective results are also comparable for all sounds; hence neglecting an issue on how well the sounds are perceived as long as they are heard. This should, however, be studied further.

Another challenge not considered in this study was the effect of traffic jams during evacuation. Especially large trucks could give shadowing effects of the sounds from the nodes, and thus lead to confusion. This effect will only occur if one is located on the opposite side of where the nodes are located, but it should be elucidated in future studies.

An earlier study [18] indicated the importance that evacuation messages has to provide simple and clear instructions. This means that one should focus on *i.* what is happening, and *ii.* what one should do. The evacuation message that was played during Experiment 2 was based on DAB messages that the Norwegian Public Roads Administration currently uses, followed by a short indication about following the sound. The message was: “*Fire in the tunnel. Evacuate immediately. Follow the sound.*” Although the principle of a simple message with clear instructions has been followed, it remains uncertain whether this is the optimal message to give. Considering that 90% of the participants chose the right direction with information provided, it is uncertain whether the potential for message improvement is large. Language choice is probably a more important factor. All participants in the experiment spoke Norwegian, and the message used was in Norwegian. Considering that people of different nationalities can use public road tunnels, the use of different languages and their effect on evacuation should be investigated further. Other factors that can also come into play are the use of female/male voice, the tone of voice and speed of speech in the audio messages.

Moreover, when as many as nine out of ten people go the right way, there is a great chance that you can get a “sheep flock/herd behaviour” effect in a road tunnel with many cars [11]. In an early phase of the fire scenario, when the evacuees are not surrounded by smoke, the few people who go the wrong way will see that “all” the others go the opposite way, and there might be a possibility that they will change direction.

5. Conclusions

The results of both experiments suggest that guidance sound signals can be used to lead evacuees in a desired direction, and that information about following the sound means that significantly more people go the right way.

The difference between the sound types was not statistically significant, thus suggesting that both sounds are satisfactory for evacuation purposes. However, preference results were provided by the subjective assessments by the participants, indicating a clearer preference for the bell and whistling sounds over the clicking sound signal. However, there is still a need for validation studies, in which further research can investigate whether the guiding sound signals can be heard under real conditions.

CRediT authorship contribution statement

Tron Vedul Tronstad: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing – Review & Editing, Project administration, Funding acquisition. **Gunnar D. Jenssen:** Conceptualization, Methodology, Validation, Writing – Review & Editing, Supervision. **Claudia Moscoso:** Formal analysis, Investigation, Resources, Writing – Original Draft, Writing – Review & Editing, Visualization. **Carl Södersten:** Formal analysis, Investigation, Resources, Writing – Review & Editing. **Eugene Zaikonnikov:** Software, Investigation, Resources, Writing – Review & Editing.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Eugene Zaikonnikov is the head of development at Norphonic AS. Norphonic was the technology designer and equipment vendor to Trafsys AS within this research project. The other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Figs. A1 and A2 show plots of the sound signals used in the experiments. The first plot shows the time lapse of the sounds, while the second shows the spectrograms. The clicking sound is a footstep on concrete with impulse like character, lasting for approx. 0.4 seconds. The bell sound is a sheep's bell with high pitch and approx. 0.7 seconds duration. The doppler sound is a custom created alarm sound with changing frequency during the playback and approx. 1.4 seconds duration.

The spectrogram shows that the clicking sound consists of short pulses with broadband spectrum, the bell sound contains ringing tones with harmonic components, and the doppler sound contains several tones that change frequency during the time lapse.

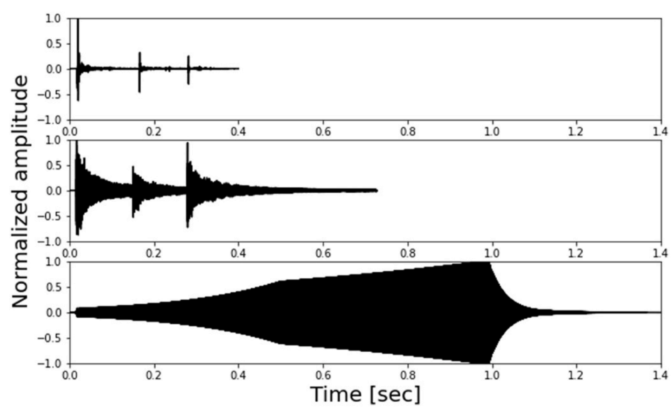

Fig. A1. Time lapse of the sounds used in Experiment 1 and 2. Upper: Clicking sound. Middle: Bell sound. Lower: Doppler sound.

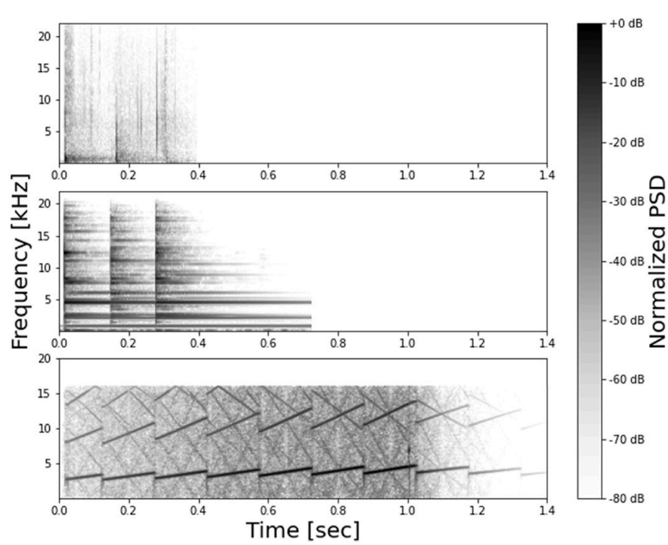

Fig. A2. Spectrograms of the sounds used in Experiment 1 and 2. The spectrograms have been created using NFFT=256, Hanning window function and 128 samples overlap, and shows a normalized power density spectrum (PSD).

Appendix B

The chi-squared (χ^2) test was calculated by comparing the results from the reference test with the observations from the sound signal cases. For the reference case 26 out of 33 participants chose to go out of the tunnel, while only 7 chose to go further in. The chi-square test statistic can then be calculated by estimating how many participants we would expect to go in a direction and compare this with the observed values from the sound experiments. An example of a contingency table for the bell sound can be seen below. 16 participants were presented with a sound signal leading them inwards into the tunnel, and 17 participants were lead outwards.

Table B.1
Contingency table for the bell sound. O = observed values. E = expected values.

	Chose the right direction		Chose the wrong direction	
Signal in (n = 16)	O = 15	E = 16·7/33 = 3.394	O = 1	E = 16·26/33 = 12.606
Signal out (n = 17)	O = 15	E = 17·26/33 = 13.394	O = 2	E = 17·7/33 = 3.606

Using the formula

$$\chi^2 = \sum_i \frac{(O_i - E_i)^2}{E_i}$$

we can find $\chi^2 = 51.28$. With one degree of freedom the p-value can be found to be $p = 4.2629e - 11$.

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