AUDITORY MARKING OF ESCAPE WAYS IN SMOKE

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ABSTRACT

Fire and smoke in a tunnel are dangerous because people get disoriented, blinded, and finally suffocate. When such a situation occurs (despite all precaution), sound beacons over the emergency exits could be a great help, reducing escape time through smoke. We let human participants "find refuge" from a road tunnel in dense (cosmetic) smoke. With "shussing" beacons, we obtained 20% success when there was no advance instruction and no demonstration. Advance instruction and demonstration raised the success rate to 69%. The paper reports new tests (with new participants) with "speaking" beacons. A success rate of 87% was obtained even without advance instruction and without demonstration. Walking speed was almost twice as fast as in the test with shussing beacons. The Dutch tunnel authorities were pleased with the results, and plan to introduce speaking beacons, as of 2006.

Smoke is very dangerous in the confined space of a tunnel, especially in densely populated areas such as The Netherlands (e.g., 40M vehicles/year through the Beneluxtunnel). Safety measures include ventilation and emergency exits that give access to spaces protected against smoke and heat. A critical question is whether motorists will go for the emergency exits, and will find them. Adequate human behaviour is critical in such time-stressed situations.

Smoke takes vision away and frightens and disorients. Motorists will consider their car as the safest place to be and, after shutting windows and ventilation, will remain seated in their cars (see also Boer, 2003, 2004 and Figure 1). Smoke takes vision away and, therefore, also the herd effect. The positive side of the herd effect is that others follow the example of one motorist getting out and walking to the emergency exit. This positive herd effect is lost in smoke. Moreover, smoke makes any emergency exit impossible to see.

Evacuation aided by directional sound seems to be the solution. The sense of hearing is unaffected by smoke. Withington developed sound beacons that produce a pulsating, hissing noise (like a diligent steam engine, or like breakers on the shore but pulsating frequently). When testing the beacons in smoke-filled environments like buildings and ships, Withington obtained success rates of over 90% (Withington, 2002; Directional sound evacuation, 2001/2002). In a follow-up, professor Withington and I tested the beacons in a smoke-filled tunnel. The success rate was 20%. We attributed this

Figure 1. Cars at the front gradually disappear in smoke, but the drivers stay in their cars (field study, Boer, 2002, 2003). [Part of these tests will be reported at the conference.]

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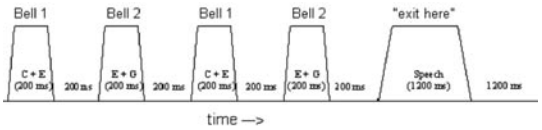

Figure 2. The signal of the beacon over time (50% silences; pattern repeated every 4 s; letters C, E, and G indicating the tones of the gamut).

to less instruction; the test participants knew only "there are sound beacons to help you" and there was no demonstration of the sound. When we told a new group of participants "there are sound beacons over the emergency exits", the success rate was 69%, still below 90% (Boer & Withington, 2005, also Boer, 2002, 2003). A demonstration of the sound is probably necessary; some test participants pointed out that the sound violated their expectations (unsolicited spontaneous remarks like "steam engine", "not a beacon at all"). It is even imaginable that the sound deterred people.

The concept of directional sound evacuation would become stronger if people would understand the sound immediately without any instruction or demonstration. The (Dutch) Centre for Tunnel Safety of the Civil Engineering Division of the Directorate-General for Public Works and Water Management commissioned TNO to develop and test such self-explanatory beacons.

NEW SOUND

Criteria

To optimize any design process, it helps to compile an explicit list of design criteria. This was done for the design of optimal sound beacons, resulting in a list of six.

The primary criterion for the new sound was self-explanation; a sound that is intuitively understood without additional explanation. This rules out the use of synthetic signals. (Synthetic signals could be mistaken for warnings.) We selected the spoken message "exit here" (English) alternating with "uitgang hier" (Dutch).

The second criterion was localizability of the sound; assessment of the position where the sound comes from should come effortless and easy. Withington's selection of noise as the basic sound source is adequate but other solutions are possible. What is really necessary is a signal with a sufficient share of high-pitched frequencies (at least up to 16 kHz) and a sufficient density of frequency components beyond 500 Hz. This permits a wealth of signals.

The third criterion was attraction quality of the sound. Signals are often judged on well-accepted features such as loudness, coarseness, harmony, and repetitiveness. These features provide a first notion of the attraction quality of sounds. We selected a dinner-bell sound: two harmonious tones repeated on a higher pitch. People are used to hear such sounds as an introduction of a verbal message. And the speech fragment "exit here" is attractive because it is a (friendly) human and, moreover, a friend who knows where the escape is.

Figure 3. Emergency exit with sound beacon on top (black box; test assistants are preparing the area; smoke is starting to develop).

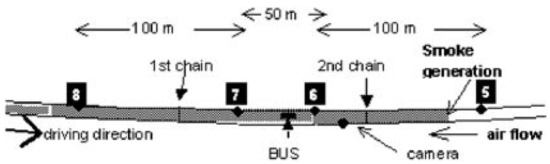

Figure 4. Test area, fenced off with chains (exits 8-5 carried sound beacons).

Criterion 4 was appropriateness to the situation. A verbal command preceded by a dinner bell suggests a formal message, which is exactly what the victims of a disaster need. Confusion with "natural" sounds is avoided. We also avoided sounds that were too happy or frivolous, like the sounds of videogames.

Criterion 5 was the effect of the sound on intelligibility of other communications. During an emergency, the tunnel operator may address the motorists by the public address system (PA). Moreover, motorists will talk to one another. It is desirable that the sound beacons do not hinder any of these communications. Unfortunately, this criterion precludes beacons that include speech. To improve the intelligibility of other verbal communications we inserted 50% silence between the sounds of the beacons.

Criterion 6 was resistance to environmental noise such as ventilator sounds. We selected a sound spectrum that differed as much as possible from such sounds.

Dinner Bells and "Exit Here"

The sound selected was a succession of two complex tones each with two basic frequencies (the tones "C" plus "E", followed by "E" plus "G"). All harmonics of both basic frequencies were included in the signal up to 18 kHz, with amplitude decreasing 3% per octave. The speech fragment received special processing to ensure localizability. Figure 2 shows the main characteristics.

TUNNEL TEST

Participants and Instruction

In the night of 29 October 2003, 75 people participated. They were recruited for "escaping from a tunnel in dense smoke", were in good health and had a driving license. There were no hearing requirements. The age range was 18-75 years, 36.4 years on average.

After arriving on the scene, the participants read (and signed) a leaflet "You will get out from the bus in the tunnel in dense smoke. Your task is: get out of the smoke, get to safety. You are on your own. Don't wait for others, don't offer assistance to others, and don't ask others for help. Do what you feel is best."

Test Area and Supervision

Test area was the C-tube of the Benelux tunnel in Rotterdam. The C-tube is 6.6 m wide with one lane of 3.5 m, and 30-cm "barriers" on either side. There were nine emergency exits along the left wall every 100 m numbered 10, 9, 8 … 2. The distance between exits 6 en 7 was half the normal distance: 50 instead of 100 m. The exits turned in the direction of the flight, and were self-closing. They could be opened with a normal (European) door-handle. The threshold was about 50 cm above the road and access was facilitated with an extra step. Step, threshold, and door were 108 cm wide; the net aperture was 90 cm wide and 200 cm high. Figure 3 shows an emergency exit.

The test area was halfway down the tunnel, around the exits 6 and 7 (see Figure 4). Chains were stretched across the roadway 25m beyond these exits. This

Table 1. Results of old (Boer & Withington) and current (bold) study (number and percentage of people arriving at the four possible endpoints).

	driving direction				
test	1st chain	exit 7	BUS	exit 6	2nd chain
B & W (old)	29	7		5	24
(n=65)	45%	11%		8%	37%
current (new)	0	1		64	10
(n=75)	0%	1%		85%	13%

Table 2. Results of old and new (bold) beacons (summarized from previous table).				
	direction of escape		destination of escape	
test	backward	forward	exit	roadway
B & W (old)	36	29	12	53
(n=65)	55%	45%	18%	82%
current (new)	1	74	65	10
(n=75)	1%	99%	87%	13%

protected participants from straying too far in the smoke. TNO personnel guarded the chains and the exits 6 and 7. Sound beacons were mounted above the exits 5, 6, 7 and 8.

A thermal imaging camera was mounted 2m high, 16 m after exit 6, looking backwards. The camera saw the wall without exits (right wall) on the left side, then the roadway, and on the right side the wall with the exits and exit 6 in particular. Figure 5 shows the camera view.

Smoke and Masks

Further down the tunnel (at exit 5) four smoke generators ("Vesuvius") produced white "cosmetic" smoke (see Figure 6a). The participants carried elementary smoke masks over nose and mouth (see Figure 6b). The airflow transported the smoke to the test area at a speed of about 0.3 m/s, against the driving direction.

Vision was 1–2m at first and decreased to ½ tot 1½ m later on. The smoke reduced the lighting somewhat: from 90–110 lux to 60–80 lux (directly underneath the lamps), from 17–37 lux to 13–28 lux (the roadway in front of the exits), and 90–105 lux to 70–80 lux (the wall around the exits). Such reductions are not very remarkable for the human eye.

Procedure

The participants arrived in two groups of 33 and 42 people, the first group around 20:00 h, the second group after 21:00 h. They read and signed the leaflet in the bus. The bus drove them over to the test area. The side windows were made opaque to prevent the participants from having any outside view. During the 15-minute ride, the instruction was repeated, questions could be asked, and the bus-exiting procedure was described.

The bus stopped between exit 7 and 6, its door 32m beyond exit 7 and 18m before exit 6. The engine remained idling. The participants left the bus at fixed intervals of about 40 s. Directly before alighting, the participant donned the smoke mask and received an id-number (a small ticket). Five to 8 minutes after the last participant had alighted, the test was over and all were escorted back to the bus.

Result

Table 1 shows where the participants ended: through an emergency exit, or at the chain across the roadway. The data of the earlier study (hissing beacons) are included for comparison.

We sum these data once for backward vs. forward escape (first chain + exit 7 = backward; exit 6 + last chain = forward) and another time for escape through emergency exit vs. escape over the roadway (exit 7 + exit 6 = emergency exit; first and last chain = roadway)--see Table 2. The trends are obvious: except for one, all participants went forward (99%) and 87% escaped through an emergency

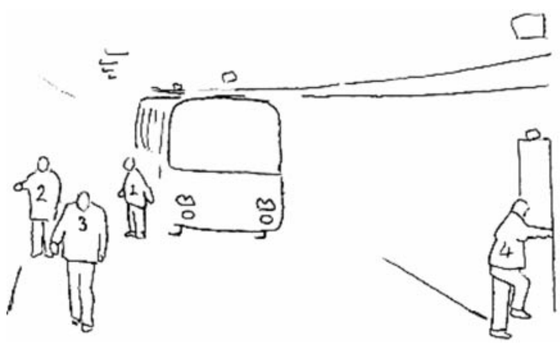

Figure 5. Camera view. After alighting (1), the participant made contact with the wall (2), or started walking along the wall (3), and crossed over to the exit (4). Other participants walked straight towards the exit (1 directly to 4). In the test, participants walked one at the time.

Figure 6. Smoke generation (left) and a test participant leaving the smoke-filled tunnel.

exit. Both trends differ significantly from the results of the old test: 45% forward vs. 99% (test for proportions $p<0.001$) and 18% emergency exit vs. 87% (id.).

The camera reveals participants alighting from the bus and walking almost straight to the camera. A few individuals hesitated over the direction but most went forward without hesitation. Forty-two participants (56%) went straight towards exit 6; that is, they crossed the roadway slantwise. The others first found orientation along the nearest wall (to their right, to the camera's left), sometimes by touching the wall, sometimes with visual contact only (see Figure 5). Some distance away from the bus, we often saw an orientation reaction: participants turned toward their left and some held their pace or even stopped. The crossing followed sometimes directly, but others continued walking along the right wall making the crossing somewhat later. A few seemed determined to ignore the sound at their left and continued along the right wall.

Walking style was greatly different. The extremes were, on the one hand, a very crouched walk and (another participant) walking at snail pace with waving hands outstretched; and, on the other hand, a very off-handed casual walk. Most walked slowly and careful, one hand outstretched. After the crossing, about five participants collided with the protruding barrier but no one fell.

Getting to the exit took on average 23 s, which is a walking speed of 0.9 m/s (considering a distance of about 20m). Delays were frequent, however, like walking sideways to establish contact with the wall, waiting and orienting, and negotiating the doorstep. These delays were included in the walking speed.

CONCLUSION

The new beacons guided 87% of the participants to the emergency exit. The result came without any advance instruction or demonstration. Additional testimony to the efficiency of the new beacons (without advance instruction) is the observation that all except one (99%) went to the nearest emergency which was in the driving direction. This goes against people's intuition to escape to where one came from. In the study with the shussing beacons, 48% went against the driving direction (Boer & Withington, 2005). More research would be needed to answer the question which (combination of the) criteria mentioned in the introduction accounted for the success of the beacons; we know only that the particular combination used here was effective.

Thermal imaging revealed the psychological difficulty of leaving the "safe" wall and crossing over to get to the sound. Motorists with a strong fear of crossing could perhaps be helped with an arrow along the wrong wall pointing across the roadway into the direction of the emergency exit (Boer, 2001).

Note that all participants alighted on the "wrong" side of the road; that is, all had to cross the roadway. In reality, about 50% of the motorists will alight on the "right" side of the road where the emergency exits are. These motorists don't have to cross the roadway. If all of them would find the emergency exits, the net result ("right" and "wrong" side together) would be over 90% success.

Current walking speed was about twice as fast as in the previous tests (speed towards exit 6 was 0.44 m/s in Boer & Withington, 2005). It should be noted that speed in Boer and Withington increased to 0.9 m/s if participants walked a 160-m distance to a chain beyond exit 8. We interpreted this as psychological confidence that grows as one continues walking without colliding against obstacles. Following this line of reasoning, the self-explaining beacons instill confidence and, therefore, promote walking speed. In real situations, motorists will walk in a tunnel filled with cars (some may be parked untidy) and debris that can lie on the road. Collisions with obstacles may occur; and motorists will loose confidence and walk with greater care afterwards. We prefer this psychological interpretation to an interpretation in terms of pure visibility (e.g., Jin, 1997).

The beacons are expected to be also effective under conditions of good visibility. We expect that the continuous repetition of "exit here" will help motorists to become aware that they are called out their car and out of the tunnel. The beacons can thus help to overcome the initial passivity of motorists involved in a disaster (Figure 1).

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