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Impact of reduced sonic boom exposure on psychophysical and cognitive performance for simulated booms presented in a realistic indoor environment

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Abstract – This study aimed to quantify, in situations representative of the daily life of European citizens, the effects of sonic boom exposure on human responses, in the case of a new generation of supersonic commercial aircraft that should emit a reduced (compared to the past generation like Concorde) but perceivable boom while flying overland. Two reduced boom simulators were affixed to the bedrooms' windows of a house located on our university campus. The simulators were used to study indoor the participants' responses to realistic "outdoor" booms. Testing took place in both the living room and kitchen because the booms caused different intensities of rattle noise in those two rooms. Participants performed various tasks (communication, working memory, drawing, valence evaluation), took three mandatory rests and filled in various questionnaires about the annoyance caused by the booms and their mood. This paper focuses on the psychophysical and cognitive performance results. The booms resulted in delayed responses in the working memory task and in the valence evaluation task, and in a momentary slowing down in the drawing task. There was no significant effect in the communication task, even though a trend for a worsening of communication efficiency was observed. Taken together, the results suggest that reduced booms can interfere with cognitive and motor tasks by capturing attention, which can momentarily divert cognitive resources away from the task at hand. These results suggest future research directions and may lead to recommendations for future sonic boom regulations.

Keywords: Sonic boom, Noise exposure, Human response

1 Introduction

Sonic boom is one of the main barriers to the renewal of civil supersonic aviation. Following pioneering theoretical works [1–3] based on fundamental Whitham's theory of sonic boom [4], a lot of progress has been achieved in the design of supersonic aircraft to significantly reduce sonic boom noise level at the ground but so far, no such low-boom aircraft exists. The Lockheed Martin X-59 Quiet Supersonic Technology demonstrator has been designed to reach a ground boom Perceived Level [5] of 75 PLdB in standard atmosphere [6]. (Note that PL is a sound level metric based on equal-sone contours. It has been pre-selected by the International Aviation Civil Organization as one of six potential best metrics for quantifying human subjective response to sonic boom noise based on a meta-analysis [7] of several perception studies.) The X-59 demonstrator is currently undergoing ground tests before its first flight planned in 2024. It will validate technologies for reducing sonic boom loudness and gather data on human responses

to low-boom exposure through community surveys (currently planned for late 2024).

In the meantime, quantitative data on the influence of reduced booms on humans in controlled environments is needed in the view to establish a regulation on sonic boom and satisfy ICAO (International Civil Aviation Organisation) General Assembly resolution A33-7 that no unacceptable situation for the public is created by sonic boom from supersonic aircraft in commercial service. They will provide useful insight as well for the future community surveys, which will have the advantage to be conducted in "real life" but will lack details about the precise sound exposure and human response to it.

The causes of annoyance of a conventional boom are now quite well understood, following several community surveys [8–11] including low amplitude booms from dive manoeuvres [12, 13], laboratory studies [14] and in-home studies [15]. The main factors identified to influence human response to sonic boom are startle, house shaking, rattle noise and damage concerns (see for reviews: [16–18]).

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In a 1993 study (published in [15]), with a low number of loudspeakers and a limited bandwidth leading to a sound reproduction far from a sonic boom shape, results indicated an increase of annoyance with the boom level, with the number of occurrences, with the age of participants, in case of boom-related startle, and when participants were sleeping or resting. A decrease of annoyance was reported when participants engaged in communication activities. More recently, using a large size simulator designed for studying indoor boom at NASA Langley Research Center, a notional model has been proposed to incorporate increased annoyance due to rattle, enlarging for a given outdoor boom level its indoor variation due to structural transmission [19]. The penalty can be typically up to 10 PLdB. Floor vibrations transmitted through a chair have similarly been evaluated as a typical 5 PLdB penalty [20].

To our knowledge, all these past studies on human response to sonic booms have focused on sensation and subjective responses such as ratings of loudness and annoyance [17]. No indoor studies have had participants engage in a cognitive or psychophysical task while they were being exposed to the booms. Even recent indoor studies dedicated to Low Booms had participants solely focused on self-evaluating the booms' subjective characteristics (i.e., annoyance: [20–22]).

This motivated the present study, which aimed at investigating the influence of reduced sonic booms on humans in the context of experimental activities inspired by daily indoor life (professional and recreational activities) and in a natural environment (typical of a European house), allowing simultaneously the so-called ecologically valid conditions [23, 24] and a high control of the noise exposure. A large effort was put into designing the boom simulators to allow the insonification of a large living room in a real house [25] and into making the experimental activities as closely related as possible to daily indoor activities, while being controlled and entertaining. Designing this study in such an ecologically valid context proved to be challenging, in particular as there was little research in the literature that could inform our choices.

We included a motor control task to test whether the booms would make participants startle, even slightly. Participants were asked to draw spirals at a quick pace. Our aim was to check whether the booms would cause irregularities or swerves in their drawing. The idea of using spiral drawing to investigate motor control and its potential disruption came from the spiral drawing test developed by Pullman [26] to measure motor dysfunctions in patients with movement disorders.

We included a working-memory task because the detrimental effect of noise on working memory is well documented [27, 28]. We chose the 2-back design, which requires the acquisition and retention of rapidly, continuously changing information [29], and is one of the most popular experimental paradigms for assessing working memory [30]. To test whether the booms could disrupt the conveying of information, we included as well a task in which conversation is involved. We adapted a task called the Diapix, originally developed by van Engen et al. [31], in which

two people are recorded while conversing to solve a “spot the difference” task. Finally, we sought to investigate the valence evaluation of the booms objectively, i.e. not by using questionnaires to collect subjective evaluations of the booms but by using the affective priming paradigm – also called “evaluative” priming paradigm [32–35] – to test whether participants automatically assigned a negative valence to the booms.

In addition to the tasks just described, we administered questionnaires to collect subjective evaluations of the booms and monitor the participants' mood at different times, including before and after rest periods. Participants had also to fill a questionnaire on their general sensitivity and attitude to noise (with a focus on traffic noise). The analysis of these questionnaires' answers are addressed in a companion paper [36].

The overall experimental design is presented in [Section 2](#). Then the four psychophysical and cognitive tasks are detailed in [Sections 3–6](#), each section presenting the procedure, the data analysis, the results and a related discussion. Discussion continues in [Section 7](#), then [Section 8](#) presents our conclusions.

2 Experimental session design

2.1 Testing environment

The testing environment was the ground floor of a three-story house located on the campus of Sorbonne University that is located in St. Cyr, west of Paris. Sonic boom presentation in the house was made possible by building two sonic boom simulators and affixing them to the outside of window frames giving into two bedrooms located on opposite sides of the house. A visual summary is provided in [Figure 1](#) while more details about the house and the simulators can be found in [25].

The study took place in both the living room and the kitchen. There was a loosely fixed glass door in the kitchen that tended to rattle strongly. Testing in both rooms thus allowed us to vary the degree of rattle: we had a Kitchen condition with strong rattle and a Living Room condition with light rattle. To further manipulate rattle, we did some of the testing in the living room with the door between the living room and the kitchen closed and the entrance door half-opened: this made inaudible the rattle from the kitchen's glass door and suppressed the living room rattle produced by the movements of the bolts against the strike of the entrance door's lock. This third room condition had almost no rattle and is referred to hereafter as the no rattle condition. However, it was only used for tasks which are not the topic of this paper (see [Fig. 2](#) and the companion paper) and will thus not be described further. Both the living room and the kitchen had daylight, which we deemed essential for ecological validity. Participants attended the study in a single afternoon session lasting about four hours, between 2 pm and 6 pm, in mid-September to late October 2020: thus, most of the testing occurred with daylight. Participants were tested in pairs (two at a time) as requested by the communication task. Participants had to move between

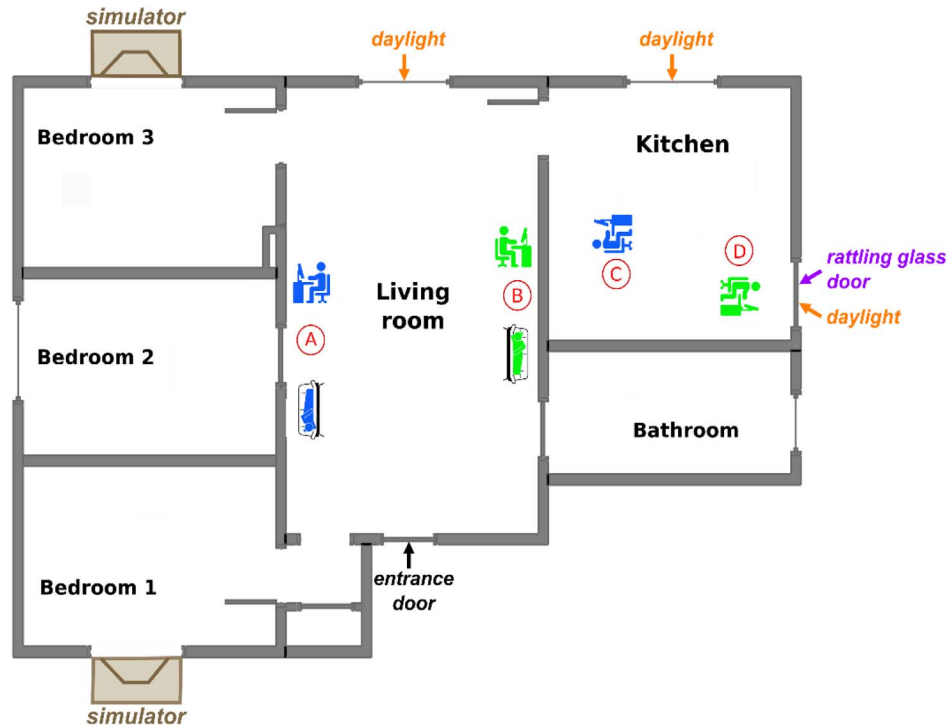


Figure 1. Map of the ground floor of the house, illustrating notably the position of the two simulators outside bedroom 1 and 3, and the testing positions (A–D, red circles) for the two participants (in blue and green, respectively) in the Living Room condition (positions A and B) and in the Kitchen condition (positions C and D).

the living room and the kitchen during the experimental session. For every pair, one participant was assigned to positions A and C (Fig. 1: living room and kitchen, respectively) and the other one was assigned to positions B and D (Fig. 1: living room and kitchen, respectively). Participants had three mandatory rest periods during the experimental session during which they were asked to have a short nap by lying down, in the living room, in either a reclining chair (position A) or a sofa (position B).

2.2 Stimuli and boom levels

We chose to put the participants in the situation of being exposed to reduced booms perceived indoor in a house with wide open windows. The boom signals were designed to have the characteristics of outdoor booms being heard inside the bedrooms 1 and 3 [25], and the open-door frames between these bedrooms and the living room acted as virtual open windows, exposing participants in the living room and in the kitchen to booms acoustically transformed by the acoustics of the living room and the kitchen (“indoor” booms). Using the bedrooms’ door frames as open windows had several advantages. First, it removed the influence of differences between window glazing, which is important because it has been shown that sonic booms are mostly transmitted indoors through windows [37]. In our house, 40-cm thick concrete walls made boom transmission through walls negligible. Second, it focused on the worst-case scenario, with the highest indoor boom level. Third, it was realistic, especially for Europe, where air conditioning

is infrequent in private housing and where people frequently live with open windows, especially in summer. For instance, it is estimated that between 50% and 75% of European people sleep with windows at least slightly opened [38].

Two boom signals of different levels were synthesised for the study to test participants in a so-called Low Boom condition and in a so-called High Boom condition. Some of the testing was also carried in a No Boom condition, without any booms presented. While full details regarding the boom simulators and how the booms were generated are provided in [25], the essential information about the two signals that were used is provided hereafter. They were *N*-waves with a peak overpressure just below 20 Pa at the simulator’s output. Their rise time was adjusted to reach the two following target “outdoor” boom levels when measured at the virtual windows (the bedroom door frames) when only one simulator was working: 62 dBA (or 78 PLdB) for the “outdoor” Low Boom signal, and 75 dBA (or 88.4 PLdB) for the “outdoor” High Boom signal.

The boom levels recorded at participants’ positions (A–D) were different from the target “outdoor” boom levels because: (1) the door between the living room and the kitchen was open (which tended to decrease the boom level), (2) the two simulators were operated simultaneously, which was needed to compensate (at least partly) the increased insonified volume and reach the desired levels (see [25]), (3) testing was carried in both the living room (where direct exposure tended to increase the boom level) and in the kitchen (where indirect exposure tended to decrease the boom level), (4) rattle noise superimposed (the lighter rattle

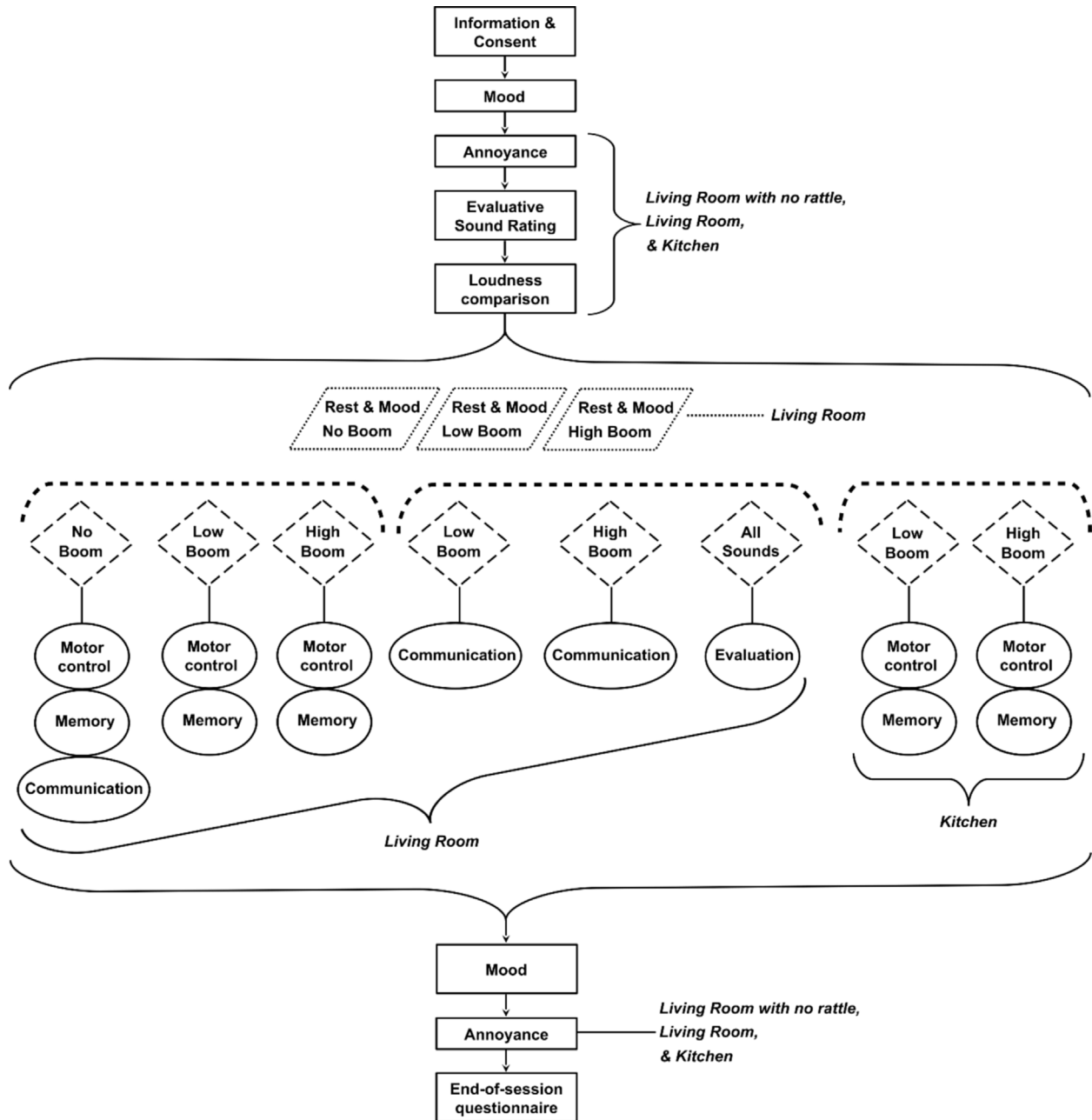


Figure 2. Flow chart of the experimental session, depicting all activities. The solid circular lines mark the psychophysical tasks (and the questionnaires attached to them), the solid rectangular lines mark the other activities (consisting of only questionnaires and ratings), the dotted parallelograms mark the three rest periods, and the dashed diamonds mark the boom conditions. For pseudo-randomisation purposes, the psychophysical tasks were organised in three groups, delimited by the three dashed opening square brackets, and within these groups the tasks were organised by boom condition. The grouping constrained the pseudo-randomised orders that could be generated. The room condition(s) in which each activity was done are displayed in italics.

from the living room window and entrance door superimposed with the stronger rattle from the kitchen glass door), (5) even in the same room and for the same boom condition, the boom level varied between the two participants' positions, (6) boom levels and variations were dependent on the selected metric, (7) there was attenuation between the so called "source" position and the participants' positions, in the living room and even more in the kitchen. [Table 1](#) compiles the boom levels (ASEL and PL metrics), for every

testing position in the living room and in the kitchen (A–D), for both the Low Boom and High Boom conditions. The shapes of the signals at the different positions and for the different conditions are provided in [Appendix A](#), along with their frequency spectrum. Note also that the "No Boom" condition is not an absolute "No noise" condition: because we do not work here in an ideal laboratory environment, there is some variable ambient noise. However, the level of this noise is always small, around 20 dB above 100 Hz. In the

Table 1. Sound levels in dBA (ASEL metric) and PLdB (PL metric) for the boom signals in all experimental conditions.

Boom signal condition	ASEL	PL
Living Room – Low Boom – position A	63.1	80.6
Living Room – Low Boom – position B	62.1	79.7
Living Room – High Boom – position A	69.5	85.9
Living Room – High Boom – position B	67.6	83.6
Kitchen – Low Boom – position C	62.2	78.5
Kitchen – Low Boom – position D	63.1	79.9
Kitchen – High Boom – position C	64.7	80.5
Kitchen – High Boom – position D	64.7	81.4

infrasound and low audible range, it can be higher but anyway much smaller than the boom level. This is discussed in detail in Cretagne et al. [25], especially in Figure 2 and its discussion.

2.3 Participants

The study was completed by 41 participants (10 male, 31 female) aged 18–69 years (18–30 years: 18, 31–45 years: 14, 46–60 years: 7, 61–70 years: 2). These demographic data are discussed in Section 7.

Participants were grouped and tested in pairs because the communication task required having two participants at the same time. There was one exception: one participant was tested on its own, and was not tested on the communication task, because the planned paired participant did not show up. Participants were compensated for their time (gift card of value 120 €). All data were anonymised to comply with European Rules for Personal Data Protection. The study was approved by the Sorbonne Université ethics committee (n° CER 2020 – 4).

2.4 General procedure

The study consisted of one experimental session lasting between four and four and a half hours. The full course of the experiment is illustrated in Figure 2.

Before starting the experimental activities, we first explained the study to the participants and we presented them the two boom signals once (in the living room), to check whether they felt comfortable listening to these sounds (they all did). We then asked them to sign an informed consent to participate, and a consent for recording their voice during the communication task. The experimental activities included four psychophysical and cognitive tasks, three rest periods during which participants were asked to nap, as well as questionnaires monitoring participants' mood, questionnaires collecting their perceptual evaluations of the booms in the context of experimental activities and in themselves, and a questionnaire on participants' general sensitivity and attitude to noise (with a focus on traffic noise). While the rest periods and the questionnaires are addressed in [36], this paper focuses on the four tasks.

The motor control task consisted in drawing spirals and is described in detail in Section 3.1. The working-memory task was a 2-back task [29] with playing cards, described in Section 4.1. Both tasks were performed in the living room and the kitchen, in five separate runs corresponding to the five following conditions: Living Room – No Boom, Living Room – Low Boom, Living Room – High Boom, Kitchen – Low Boom, and Kitchen – High Boom.

The communication task was adapted from the DiapixUK [39] and involved descriptions of images to spot differences (see the full description in Sect. 5.1). It was performed in the living room only, in three separate runs corresponding to the three following conditions: Living Room – No Boom, Living Room – Low Boom, and Living Room – High Boom.

The valence evaluation task was a cross-modal evaluative priming task [35] and is described in Section 6.1. It was performed in the living room only and had the two boom levels mixed in the same run.

The order of the runs was pseudo-randomised across tasks so that participants would alternate between different tasks to avoid boring and discouraging them. Pseudo-randomisation was chosen over full randomisation to minimise back-and-forth moves between the living room and the kitchen: participants did either all the living room tasks and conditions first and all the kitchen tasks and conditions second, or the reverse.

2.5 Apparatus

The apparatus used for booms generation and presentation is described in the technical paper [25]. All experimental tasks were performed on two laptops (moved when needed between the living room and the kitchen) and were implemented with the Python experimental software PsychoPy [40], except for the motor control task that was implemented in Movalyzer (Neuroscript LLC, Tempe, AZ, USA) using a Wacom stylus and digitizer (Wacom Co., Ltd., Kazo, Japan). The triggering of the booms was controlled from a desktop computer in the living room by the experimenter, by running the same experimental scripts as on the two laptops (except during the valence evaluation task, see Sect. 6.1). The experimenters launched the experimental activities on the participants' laptops and the desktop computer by pressing keys simultaneously on the desktop's keyboard and on two Bluetooth keyboards connected to the laptops. The clocks of the three computers were synchronised at the beginning of each session.

3 Motor control task

3.1 Procedure

We used the spiral drawing test developed by Pullman [26] to measure motor dysfunctions in patients with movement disorders. Participants were asked to draw six spirals in 25 s, a time interval during which one boom was presented randomly. Participants were instructed to try to draw the six spirals while keeping them as regular

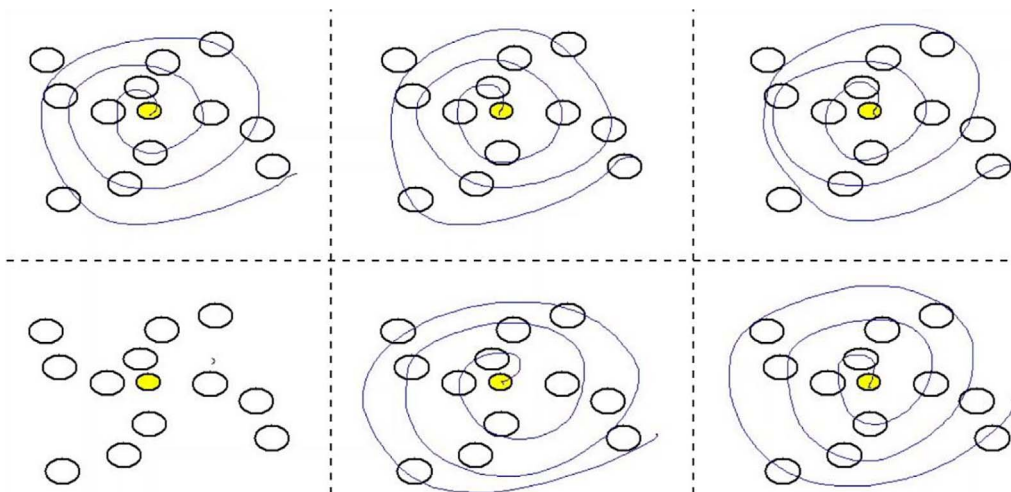


Figure 3. Example of a 25-s trial. In this example, the participant managed to complete five of the six spirals. The participant had to draw each spiral counter clockwise, starting from the centre yellow circle. Participants had to start with the top-left spiral and move in a clockwise order, hence the last spiral of the trial was on the bottom-left. The dotted lines were not displayed for the task; they have been added to illustrate the data analysis presented in the next section.

as possible. They had to draw the spirals passing through circles displayed on the computer screen, to get similarly sized spirals from all participants. One 25-s interval constituted a trial. The short trial duration was chosen to make the task difficult and keep the participants drawing quickly, which we assumed would make boom-induced swerves more likely. To illustrate the task, Figure 3 displays one trial from one participant. Participants completed six trials separated by 5-s breaks, hence the total duration for one run of the task was 2 min 55 s. To vary the task and maintain participants' interest, spirals had to be drawn counter clockwise in the first three trials and clockwise in the last three trials. The pen input (x and y coordinates, and axial pressure) was recorded (at a 133-Hz sampling rate).

3.2 Data analysis

In a first analysis, we counted the number of spirals that participants drew for each of the four combinations of the Low Boom/High Boom conditions and the Living Room/Kitchen conditions, as well as for the No Boom condition. As participants had to draw the spirals passing through circles displayed on the computer screen, we were able to include incomplete spirals in our count by counting the number of circles passed through, and thus the number of spirals is not necessarily an integer. The number of spirals for the six trials of a run were averaged together. It was counted in the No Boom condition and then compared to the four other conditions with Bonferroni-corrected paired t -tests. Due to technical problems, the drawing data were not collected for two participants (2 males, aged 41 and 65 years), hence this analysis was performed on 39 participants.

In a second analysis, we divided the drawing space into six equal drawing zones, each including one of the six spirals, as illustrated by the dotted lines on Figure 3. We used the pen input data to calculate, for each trial, the time

spent on the zone during which the boom had been presented (called zone #0) and compared this time to the time spent on the zones that immediately preceded (called zone #-1) and immediately followed (called zone #1). For the statistical analysis, we transformed participants' individual response times to z -scores, to minimise between-participant variability, by subtracting the mean of the participant's response times from each individual response time and by dividing by the standard deviation. We then averaged together the times spent on non-boom zones (zone #-1 and zone #1) and compared them to the times spent on the boom zone by performing a three-way ART ANOVA [41] with the zone numbers (#0/mean of #-1 and #1), the room conditions (Living Room/Kitchen) and the boom conditions (Low Boom/High Boom) as independent variables. For significant effects, we calculated the standardised mean differences to measure effect sizes (d_s : [42]).

Due to technical problems, we failed to record the boom onset time for one or two conditions for 10 participants. This data loss added to the 2 participants lost for the first analysis. Hence, the data set for the second analysis included 29 participants (4 male/25 female, aged 18–56 years [18–30 years: 15, 31–45 years: 8, 46–60 years: 6]). Not every participant had both a zone #-1 and a zone #1 because participants drew at different speeds and because the timing of the boom presentation was randomised.

3.3 Results

The first analysis, on the number of spirals drawn, did not show any statistical differences between any of the four conditions with booms and the No Boom condition. The means and 95% confidence intervals for the five conditions were indeed very similar: 4.65 ± 0.31 (No Boom), 4.68 ± 0.30 (Living Room, Low Boom), 4.54 ± 0.29

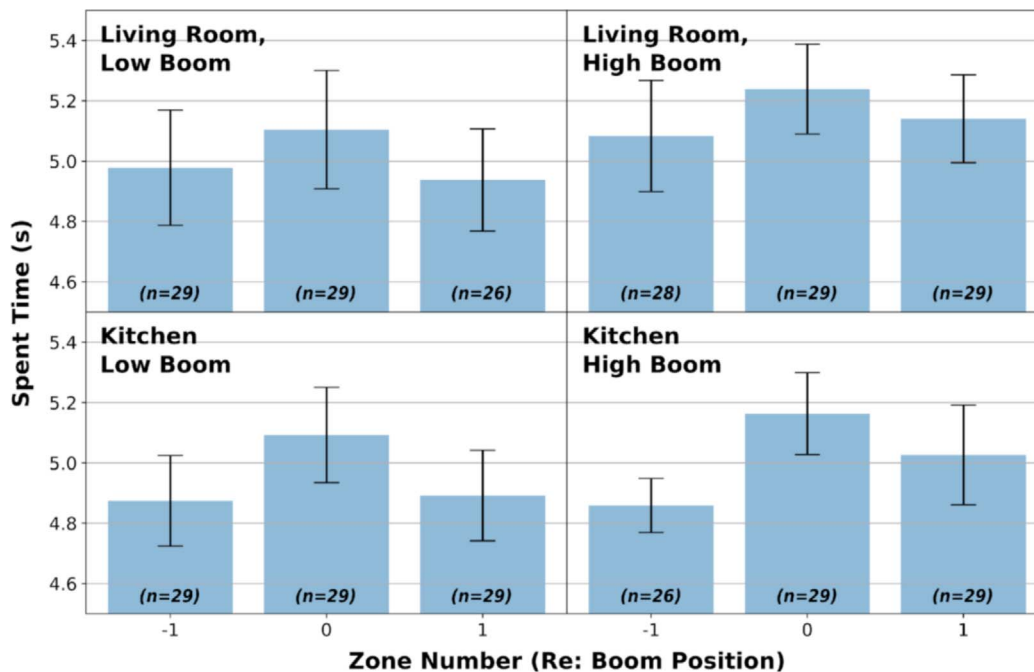


Figure 4. Motor control task. Time spent (in seconds) on zone #-1, zone #0, and zone #1, averaged across participants, plotted for the four conditions in which booms were presented. The number of participants for each zone and each condition is indicated between brackets at the bottom of each bar. Error bars represent standard errors of the mean. We chose to plot the times in seconds for better readability, but the statistical tests were carried on the z-scores.

(Living Room, High Boom), 4.67 ± 0.28 (Kitchen, Low Boom), and 4.67 ± 0.31 (Kitchen, High Boom).

The second analysis, on the time participants spent on zone #0 compared to the average time for zone #-1 and zone #1, yielded a main effect of the zone numbers [$F(1, 196) = 5.16$; $p < 0.05$; $d_s = 0.34$]: participants spent significantly more time on zone #0, the zone during which a boom was presented, than on zone #-1 and zone #1, and this could be observed for all four conditions in which booms were presented (between 1.9% and 6.3% depending on the condition, when averaged across participants; Fig. 4). No other statistical effects were observed.

3.4 Discussion

The main takeaway from this task is that reduced sonic booms can negatively influence performance in a motor control (drawing) task, as we observed that participants spent more time on zone #0 than on zone #-1 and zone #1. Performance was disturbed for all four conditions in which booms were presented. Neither the change in boom level nor the presence of rattle (in the kitchen) significantly modulated the effect of the booms. To investigate further the effect of the rattle, we took advantage of the fact that the rattle noise was louder at position D (next to the kitchen glass door: see Fig. 1) than at position C and compared the boom disturbance in the kitchen between participants seated at these two positions. Being seated at position D did not result in greater boom disturbance, which suggests that rattle per se was not the dominant factor in boom disturbance. However, the respective influence of sound level

and rattle level need to be clarified in future research: in our study, rattle and level could not be manipulated independently (a higher boom level caused more rattle), which limits the conclusions that can be drawn from our data. Future research should also investigate which psychophysical processes may be affected by reduced booms. In the present study, the greater times spent on zone #0 may not necessarily reflect an effect on motor control; they could instead reflect an effect on motor planning. We tried and failed to detect boom-triggered momentary irregularities or swerves in the participants' drawings (using the recorded pen coordinates to calculate the acceleration, the jerk, and the pressure variation as a function of time). This suggests that the reduced booms might not have caused participants to momentarily lose control of the pen, but rather might have made them hesitate as to what or where to draw next. In other words, the reduced booms might have disturbed participants' cognitive control rather than their motor control.

4 Working-memory task

4.1 Procedure

Participants performed a standard "2-back" task (see [43] for a review), using playing cards as items to make the task a bit more entertaining. Twenty playing cards were displayed one after another at the centre of a computer screen, for 1.5 s each, and participants had to constantly compare the card on display to the penultimate card displayed, and judge whether it was the same or not.

Although participants were asked to memorise and compare the cards, the suits were irrelevant as, for each series of 20 cards, any given number was always associated with only one suit. This was done to avoid having a too difficult task. Each series of 20 cards had six “targets”, i.e., cards that were indeed the same as the penultimate card displayed. The position of the targets within a series was randomised with the constraint that they should be split equally between the first 10 cards and the last 10 cards of a series. One boom was presented randomly between the 8th and the 14th card of each 20-card series. Six series were presented per experimental condition, with a 30-s break between series. Hence, the total duration for one run of the task was 5 min. Percentages of correct responses and response times were collected.

4.2 Data analysis

One participant (1 female, 46 years) did not use the instructed response keys, hence only 40 participants were included in the data analysis. For two of those 40 participants, in the Living Room – High Boom condition, data were erroneously recorded for four series of cards instead of the six series planned. Data analysis made use of all cards, not only targets. Cards for which the participant’s response had been quicker than 150 ms were discarded as anticipations.

We assessed participants’ performance by calculating percentages of correct responses and mean response times for correct responses. The twenty cards within each series were re-numbered so that the card on display when the boom occurred was always numbered “0” (card #0). Then, the newly aligned (relative to the boom’s position) series from one condition were averaged together. Mean performance on card #0 and the following card (card #1) was compared to the mean of the performance for the four cards preceding the boom (cards #-4 to #-1), which served as a “baseline” performance within a series. For the statistical analyses, we first transformed participants’ individual response times to z -scores to minimise between-participant variability, using the grand mean and standard deviation of a participant’s responses in all five conditions. We then performed a three-way ART ANOVA, using as independent variables: the card position in time relative to the boom (mean of card #0 and card #1/mean of cards #-4 to #-1), the room conditions (Living Room/Kitchen), and the boom conditions (Low Boom/High Boom). For significant effects, we calculated the standardised mean differences to measure effect sizes (d_s ; [42]).

4.3 Results

Performance, as indexed by percentages of correct responses, was good: the mean percentage of correct responses, when averaged across all participants and conditions, was 87.3%, with the worst-performing participant having a mean percentage of 68.9% and the best-performing participant having a mean percentage of 96.8%. We did not

find any effect of the booms on the percentages of correct responses. The means and 95% confidence intervals were very similar for the five conditions: 88.41 ± 3.49 (No Boom), 85.65 ± 4.03 (Living Room, Low Boom), 82.93 ± 4.65 (Living Room, High Boom), 88.28 ± 3.42 (Kitchen, Low Boom), and 90.11 ± 3.27 (Kitchen, High Boom).

However, the correct response times for cards #0 and #1 were visibly influenced by the boom, at least for the two Low Boom conditions as illustrated in Figure 5, which shows the correct response times as a function of the card number for the four conditions in which booms were presented. We observed a main effect of the card position relative to the boom [$F(1, 273) = 4.91$; $p < 0.05$; $d_s = 0.28$], a main effect of the boom condition [$F(1, 273) = 4.21$; $p < 0.05$; $d_s = 0.22$], and a main effect of the room condition [$F(1, 273) = 8.31$; $p < 0.01$; $d_s = 0.28$]. There were no significant interaction effects. The three main effects reflect, respectively, longer correct response times for cards #0 and #1 than for the four cards preceding the boom, longer correct response times in the Low Boom condition than in the High Boom condition, and longer correct response times in the Living Room condition than in the Kitchen condition.

4.4 Discussion

The main takeaway from this task is that reduced sonic booms can disturb people’s memory processes, as we observed longer response times for cards #0 and #1 than for the four cards immediately preceding the boom presentation. We did not, however, observe longer response times for card #2, which indicates that the booms did not prevent the memorisation of card #0 but rather disturbed memory processes related to the maintenance in memory of card #-2 and card #-1 and/or processes related to the comparison of cards #-2 and #-1 to cards #0 and #1. The boom-triggered increase in response times was more visible for the two Low Booms conditions than for the two High Booms conditions (Fig. 5, even though the interaction between the card position relative to the boom and the boom condition was not significant). In addition, the Kitchen – High Boom condition differed notably from the other conditions in that participants responded quicker in that condition, irrespective of the relative card position. To try to gain more insight on the differences between conditions, we plotted results for the four participants’ positions (A–D, see Fig. 1) separately. Figure 6 plots the z -scores conversions of correct response times averaged over the four cards preceding a boom: it reveals that responses were the fastest for participants seated in position D, in both the High Boom and the Low Boom conditions, and for participants seated in position C, in the High Boom condition only. This points to an effect of the rattle noise from the kitchen glass door on participants’ performance independently of the booms: participants were better (quicker correct responses) when sitting next to the rattling kitchen door (position D) for the two boom level conditions, and also when sitting in the kitchen but a bit farther from the rattling door (position C) in the High Boom condition (which would have been triggered a

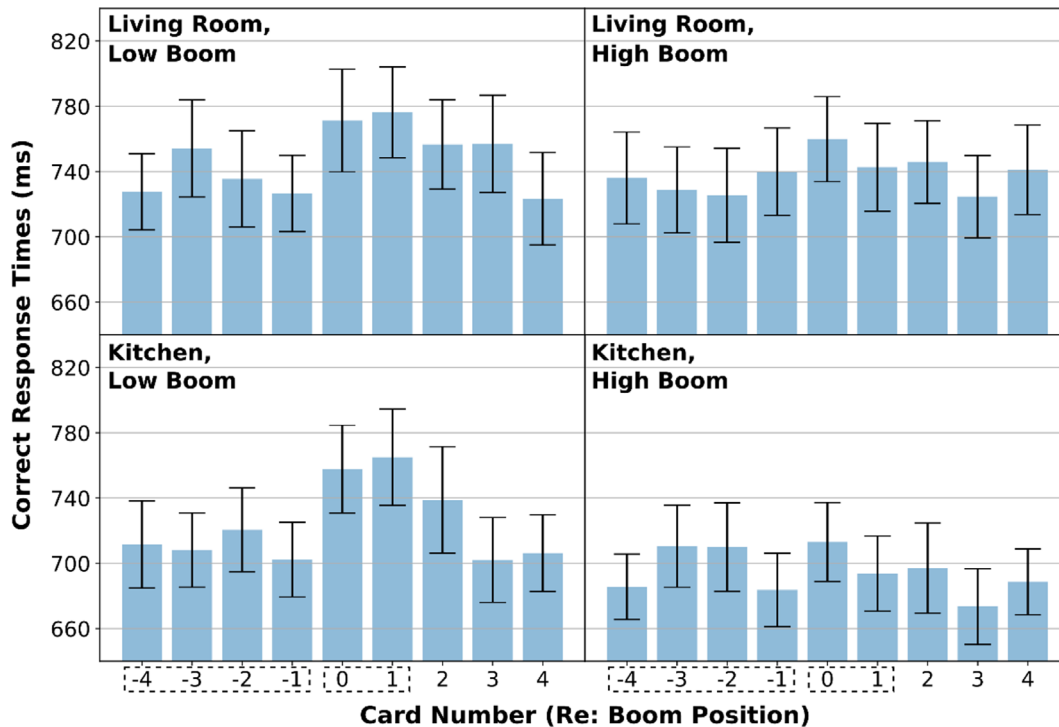


Figure 5. Working memory task. Correct response times (in ms) averaged across participants are plotted for the four conditions in which booms were presented. Error bars represent standard errors of the mean. We chose to plot response times for better readability, but the statistical tests were carried on the *z*-scores. The dotted squares in the *x*-axis legend around cards #-4 to #-1 and cards #0 and #1 illustrate that it is the means for these two groups of cards that were compared in the statistical analysis.

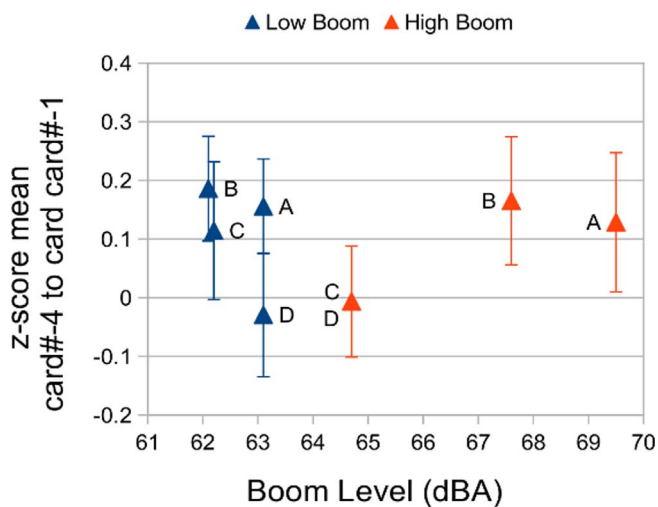


Figure 6. Correct response times converted to *z*-scores, split by participants’ seating positions.

slightly louder rattle noise than the Low Boom condition). Differences in boom levels in the quasi absence of rattle noise (positions A and B) did not result in similar performance enhancements as the average *z*-scores on Figure 6 are similar for the A and B positions in both the Low Boom and High Boom conditions, even though the ASEL level difference between Low Booms and High Booms was twice as large in the living room as the level difference in the kitchen

(~5–6 dBA vs. ~2–3 dBA). The rattle noise in the kitchen made the booms perceptually more salient and potentially more distracting, especially in position D. Our hypothesis was that the stronger distraction would result in lower performance in the kitchen than in the living room, which is the opposite of what we observed. However, it is not uncommon in experimental psychology to observe an inverted U-shape relationship between task difficulty and task performance [44]. It is conceivable that the exposure to more salient distractors in the kitchen might have led to enhanced cognitive mobilisation, thus resulting in better performance. Participants knew beforehand that the rattle was stronger in the kitchen because they had already heard the booms at the same positions at the beginning of the experimental session (during the evaluative sound rating task, see Fig. 2). Greater cognitive mobilisation might also have led to a better attentional suppression of the distractors, or in other words to a smaller effect of the booms.

5 Communication task

5.1 Procedure

We translated to French a subset of the picture materials from the DiapixUK version of the task, developed by Baker and Hazan [39]. The DiapixUK material consists of pairs of pictures, drawn in a “cartoon” style. The two pictures of a pair are identical except for 12 differences. Two participants are each given one of two pictures of a

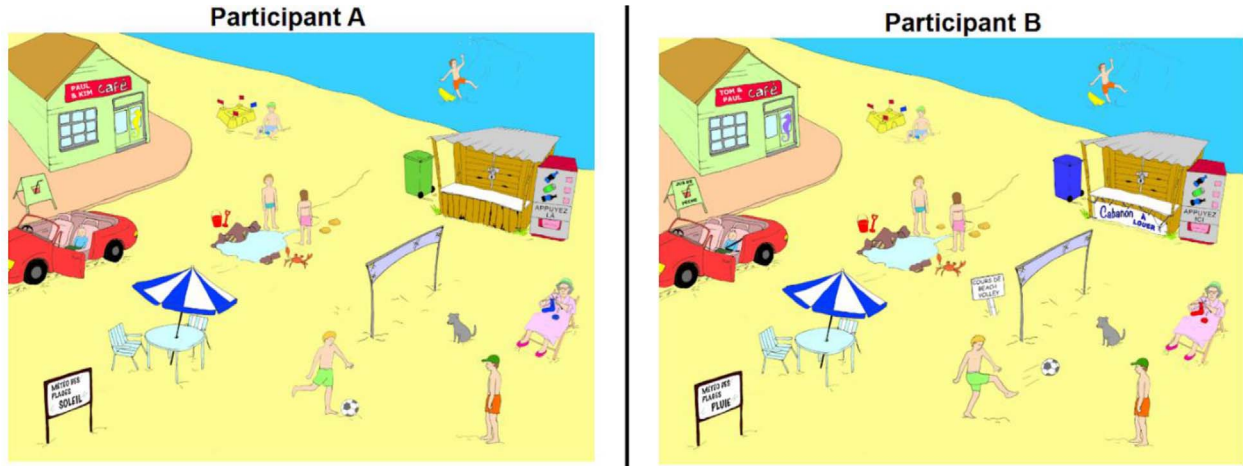


Figure 7. One of the four pairs of pictures used in the communication task.

pair (they cannot see the other picture), and their task is to find the 12 differences by verbally communicating with each other. We used four pairs in the present study: one for practice and three experimental pairs, one for each boom condition (No Boom, Low Boom and High Boom). [Figure 7](https://zenodo.org/communities/diapix) displays one of the pairs used in the experiment (the four total pairs are available on <https://zenodo.org/communities/diapix>). The three experimental pairs were allocated to the boom conditions randomly. Participants had 5 min to find the 12 differences. For the Low Boom and High Boom conditions, booms were presented randomly, with an average interval of 40 s between two successive booms. For practical reasons, this task was only conducted in the living room (with the kitchen door opened and the living room entrance door closed, hence with rattle).

5.2 Data analysis

For each pair of participants ($N = 20$) and each applicable boom condition (No Boom, Low Boom, High Boom), we estimated communication efficiency by dividing the number of differences found by the time taken to find all of them (or 5 min if the participants had not found all 12 differences). Communication efficiency was not normally distributed in the No Boom condition, so we performed a one-way ART ANOVA [41] with the boom condition as the independent variable.

5.3 Results

Communication efficiency, averaged across the 20 pairs of participants, is plotted in [Figure 8](#). Visually, communication efficiency seemed greater in the No Boom condition than in the Low Boom condition but was similar in the No Boom and in the High Boom conditions. The ART ANOVA did not show an effect of the boom condition, so we cannot reject the null hypothesis of no effect of the booms on communication efficiency. Fourteen out of 20 pairs of participants had greater communication efficiency in the No Boom condition than in the Low Boom

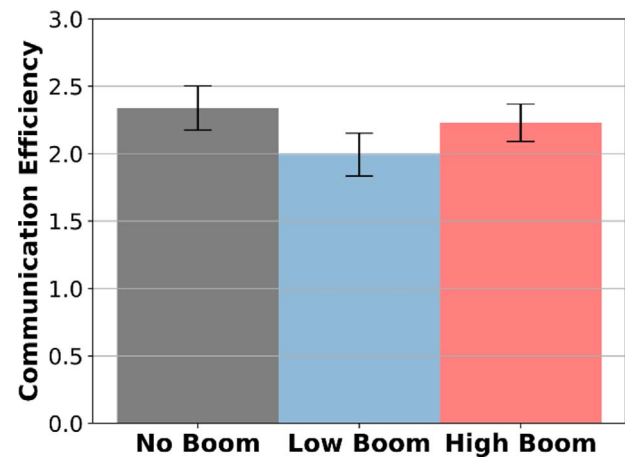


Figure 8. Communication efficiency (number of differences found divided by time spent on the task) during the three conditions of the communication task, averaged across participants. Error bars represent standard errors of the mean.

condition, but only 10 out of 20 pairs had greater communication efficiency in the No Boom than in the High Boom condition.

5.4 Discussion

The interpretation of the communication task is limited by the fact that, because participants were tested by pairs, we had less statistical power than for the other tasks (sample size = 20 pairs). Tasks performed in pairs maximise participants' engagement, which is useful in long experimental sessions, but future studies should investigate potential effects of reduced booms on individual communication performance. In the present study, the Low Booms, but not the High Booms, decreased communication efficiency. Performance being affected by Low Booms but not by High Booms is reminiscent of the results for the working memory task. Thus, similarly, we hypothesise that

cognitive mobilisation might have been greater in the High Boom condition. This is consistent with the questionnaire ratings for the task concentration question [36], which were higher for the High Boom than for the Low Boom. Performance being affected by Low Booms but not by High Booms contrasts with the results for the motor control task (Sect. 3.1), but this is not inconsistent with the cognitive mobilisation hypothesis because the motor control task was not a cognitive task and should have mobilised much less cognitive effort.

6 Valence evaluation task

6.1 Procedure

Participants performed a cross-modal evaluative priming task [33–35]. In an evaluative priming task, participants must categorise target items, as quickly and as accurately as possible, according to their valence (positive or negative). Each target is preceded by a prime item whose valence is either congruent with the target’s valence or not. The expected results are that congruent targets should be categorised better and faster than incongruent targets. This congruence effect, called a “priming” effect, suggests that the valence of the prime has been evaluated automatically (i.e., without the participants’ awareness since it is not needed to do the task and they are typically instructed to not pay attention to the primes), and that the automatic valence evaluation of the primes interferes with the subsequent valence evaluation of the targets. With this task, we sought to test whether the valence of the reduced booms is automatically evaluated and interferes with the valence evaluation of target words.

Most studies using the evaluative priming task have focused on the visual modality. However, a cross-modal version of the evaluative priming task using auditory primes has been investigated by Scherer and Larsen [35], using as primes unpleasant and pleasant sounds taken from the International Affective Digitized Sounds database (IADS-2; [45]). The present study used a similar experimental design as Scherer and Larsen [35] with the double aim to replicate their finding of a cross-modal evaluative priming and extend it to reduced booms, which are arguably unpleasant sounds. Six positive and six negative French words were selected from the EMA database (EMotionality base according to Age; [46]) based on their valence norm. Eight pleasant and unpleasant sounds were selected from the IADS-2 [45] based on their valence norm. As priming task effects decrease as the duration of the prime increases [35], 2-s clips were extracted from the selected IADS-2 sounds and those clips were used as the primes. Our two reduced booms were added to this pool of sounds (Low Boom and High Boom). Each possible “sound–word” pair was used once (120 trials in total). The order of the “sound–word” pairs was pseudo-randomised. A trial started with the presentation of a 2-s prime while a fixation cross was displayed at the centre of the screen, which was replaced by a target word immediately after the end of the 2-s prime. The target word stayed on display for 150 ms then was replaced by a masker (line of

asterisks) for 550 ms. The participant had the 700-ms interval between the end of the prime and the end of the masker to respond by pressing a key on the keyboard. The participant’s response terminated the trial and triggered the start of the next one. If the participant did not answer within the 700-ms interval, a 500-ms warning was displayed on the screen to encourage the participant to answer more quickly. Participants had a 30-s pause after 40 trials and after 80 trials. The total duration of one run of the task was thus 7 min 24 s or less. As the participant’s response terminated the trial, the two participants of an experimental session did not remain synchronised over the course of the task. In order to get trials synchronised with the sounds for both participants, we ran the task twice, once with the sound interface system plugged to one of the participant’s laptops, and once with the sound interface system plugged to the other participant’s laptop. For each participant, only the data collected when the sound interface system was plugged into their laptop was analysed.

6.2 Data analysis

For the 41 participants, we assessed performance by calculating percentages of correct responses (CRs) and mean response times for correct responses (RTs). Responses quicker than 150 ms were discarded as anticipations and responses longer than 700 ms were discarded as omissions. Data for the four pleasant IADS-2 primes were averaged together, as were the data for the four unpleasant IADS-2 primes. Two ART ANOVAs were conducted, one with the CRs and one with the RTs as the dependent variable. Both analyses used two independent within-participant variables: the prime type (negative prime, positive prime, Low Boom, High Boom) and the prime/target congruency. For prime/target congruency, we treated the booms as negative sounds, hence trials were categorised as congruent for negative targets following negative IADS-2 primes and booms, congruent for positive targets following positive IADS-2 primes, incongruent for negative targets following positive IADS-2 primes, and incongruent for positive targets following negative IADS-2 primes and booms. As previously, we calculated the standardised mean differences to measure effect sizes (d_s ; [42]).

6.3 Results

We observed a main effect of the prime type on both the percentages of correct responses [$F(3, 280) = 11.54$; $p < 0.001$] and the correct response times [$F(3, 280) = 9.19$; $p < 0.001$]. As can be seen on Figure 9, the booms elicited higher percentages of correct responses and greater response times than the unpleasant and pleasant IADS-2 sounds. The standardised mean differences between the two boom signals and the eight IADS-2 sounds were $d_s = 0.14$ for the correct responses and $d_s = 0.26$ for the response times. There was no priming effect: accuracy was not better and correct responses were not faster when the valence of the visual word targets (positive/negative)

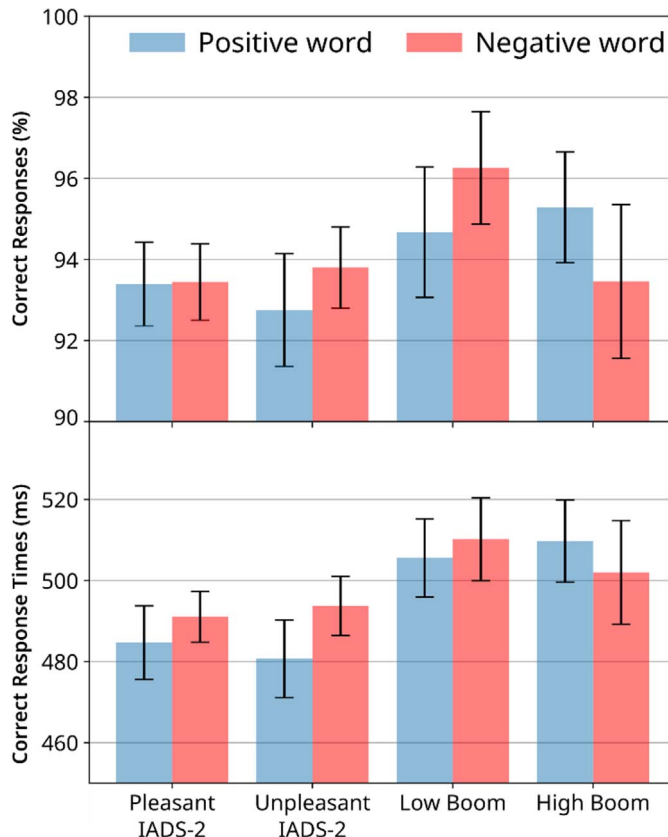


Figure 9. Cross-modal evaluative priming. Percentages of correct responses (top) and correct response times (bottom), for positive and negative visual words, as a function of the preceding auditory primes (pleasant IADS-2, unpleasant IADS-2, Low Booms and High Booms). Error bars represent standard errors of the mean.

matched the valence of the auditory primes (pleasant/unpleasant) than when they did not.

6.4 Discussion

Contrary to our hypothesis, we did not observe a priming effect. Instead, we observed slower but more correct responses for targets – both positive and negative – that were preceded by booms rather than by IADS-2 sounds. Observing slower responses when booms were presented is reminiscent of the slowdowns observed in the motor control task and in the working-memory task. The literature on automatic affective evaluation provides a hypothesis that could help explain the slowdowns in all three tasks. According to the automatic vigilance hypothesis [47], negative stimuli trigger greater engagement of attentional resources, possibly as an adaptive behaviour meant to monitor the environment for potential danger. If the booms triggered automatic vigilance mechanisms, attentional resources should be momentarily diverted away from all task-relevant cognitive processing and focused on monitoring the environment for negative stimuli. In the motor control task, this could mean a momentary weakening of the executive processes of motor planning. In the working-memory task, there would be fewer cognitive resources available to

maintain the cards in memory and compare them to previously seen cards. The case of the valence evaluation task is different because, unlike in the other tasks, monitoring the environment for negative stimuli was task relevant. For this task, the greater engagement of attentional resources on negative stimuli could have been expected to facilitate the valence categorisation of the targets. A facilitated valence categorisation would be expected to translate to both an increase in accuracy and a decrease in response times. Instead, we observed an increase in both accuracy and response times. As hypothesised previously by Gao et al. [33], it is possible that “people in a negative context are more careful not to make a mistake, such that the amount of information needed to make a decision is larger”. The negative contexts created by the booms might have triggered a shift in the participants’ decision criterion, meaning that they would have taken the time to accumulate a bit more evidence in favour of one of the two response alternatives before making their decision.

As to why we did not observe a priming effect, several factors may have contributed to this negative result. Firstly, it should be noted that Scherer and Larsen found an effect only for the unpleasant primes, not for the pleasant primes. Thus, it is not surprising that we did not see an effect for the pleasant primes. We still decided to include

pleasant primes in our study because we also collected subjective ratings of the sounds' pleasantness and we wanted to contrast pleasant and unpleasant sounds (reported in the companion paper). Secondly, priming effects are stronger when the "attitude accessibility" [48] of the primes is stronger, which means when the primes are strongly associated with a positive/negative attitude and are quickly evaluated as being so when presented. This may not have been the case in the present study because the booms were unfamiliar, and the other sounds had their sound quality compromised by the reproduction system being designed for boom reproduction. Thirdly, priming effects are stronger when the stimulus-onset asynchrony (SOA: the time between the start of the prime and the start of the target) is short, in the range of a few hundred milliseconds [48]. Scherer and Larsen [35] observed a priming effect with 1-s extracts (and thus 1-s SOAs) of sounds from the same sound database we used (IADS-2; [45]), but we chose to double this time (2-s extracts and 2-s SOAs) to get more recognisable primes with our sound system. This might have been a mistake. There is evidence that the valence information of the IADS sounds can be automatically extracted with extracts as short as 200 ms [49]. Future investigations could try again to assess the automatic evaluation of low sonic booms with the priming paradigm but using shorter priming sounds.

7 Discussion about the participants

Data collection was carried during the Covid pandemic, between two lockdowns, and we prioritised recruitment speed over balancing the groups for sex. We also did not have any a priori hypothesis on sex. However, recent literature suggests that the sex imbalance may have impacted the results. Abbasi et al. [50] compared cognitive performance, psychophysiological responses, and self-rated annoyance and fatigue between male and female participants continuously exposed to fan noise and observed that the latter were more sensitive to noise. Similarly, Töpken and van de Par [22] pointed out that female participants rated reduced sonic booms as more annoying and louder than male participants. Since we tested mostly female participants, our results might overestimate the average effects the reduced booms could have on the general population. With that in mind, we looked at the effects of the booms observed in this study for the male and for the female participants separately. For the motor control task, when averaging across conditions, female participants ($N = 25$) spent 160 ms more (participants' average) in the zone in which the boom appeared compared to the neighbouring zones, whereas male participants ($N = 4$) spent only 73 ms more (on average). For the working memory task, when averaging across conditions, responses for the female participants ($N = 30$) were longer by 33 ms for card #0 and #1 than for the four cards preceding the boom (participants' average), whereas the same figure for the male participants ($N = 10$) was only 17 ms. Our data is thus consistent with the possibility that the effects of reduced booms

may be greater for females than for males, but we cannot be conclusive because of the sex imbalance in our study.

8 Conclusion

Previous studies on human response investigated subjective self-evaluation of boom responses such as ratings of loudness and annoyance. The main objective of this paper was to examine human response of participants engaged in cognitive or psychophysical tasks while being exposed to indoor booms. These activities were chosen to be related as closely as possible to daily indoor activities, while being controlled and entertaining. They were selected from literature, but, to our knowledge, none had ever been used in the context of boom or impulsive noise exposure. We included a motor control task, a working-memory task, a conversation task and an affective cognition task. Participants' responses to boom exposure during rest periods as well as their answers to various questionnaires will be addressed in a companion paper. Our results, summarised in Appendix B, show that boom exposure increased the time spent on executing the motor task, increased correct response times in the working memory task and the valence evaluation task, and decreased communication efficiency – but in this case surprisingly only for the lowest boom levels. All of the observed statistical effects were small effects, according to Cohen's guidelines for interpreting his effect size metrics (all $d_s < 0.5$; [42]). Effects were observed at moderate levels (60–70 dBA or 77–86 PLdB), and a higher boom level did not seem to necessarily result in worse task performance in our experimental context. One partial explanation for this is that the propagation into a building tends to considerably reduce the differences between boom levels when observed indoor compared to outdoor. Thus, the 13 dB difference between the two booms at the source (virtual window) turned into only 6–7 dB difference in the living room and 2 dB in the kitchen. Therefore, more indoor studies in ecological setups are needed to clarify the boom level-dependence as well as the respective contributions of boom and rattle on performance. Future research, including community surveys, should also clarify the potential impact of reduced booms on attention and motor control in potentially hazardous daily-life situations (such as cooking, handiwork, driving) or professional life situations (an operating surgeon for instance), and investigate the long-term impact of reduced booms on cognition, notably the potential impact on school children's cognitive development. We did not observe any startle from the booms in the motor control task. However, given the potentially large number of people exposed to reduced sonic booms from future aircraft and the seriousness of potential startle in some daily-life situations, future studies should keep investigating possible startle from reduced sonic booms. In addition, as our data suggest that reduced booms might affect women more than men, future studies should specifically test for potential gender differences. Finally, even though this study targeted mostly booms of relatively low levels, as could be expected from future supersonic

aircraft, further research should also investigate psychophysical and cognitive performances of people exposed to other types of impulsive noises of various levels.

Conflict of interest

Author declared no conflict of interests.

Data availability statement

The data are available from the corresponding author on request.

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Appendix A

Signals

Figure A.1 shows the measured signals at positions A and B in the living room, and Figure A.2 at positions C and D in the kitchen, when operating the two simulators simultaneously with doors between the living room and bedroom 1, bedroom 3 and kitchen kept open. Either in the living room or in the kitchen, the wave shapes were rather similar from one position to another one, and did not differ much from the Low Boom case to the High Boom one. However, the wave shapes significantly differed in the living room (Fig. A.1) from the *N*-wave shape measured at the virtual windows (see [25]) because of room effects. A first shock was always clearly visible. However, because simulators were not equidistant from positions A nor B, booms emanating from the two virtual windows did not arrive exactly at the same time at these two positions, thus increasing the rise time and smoothing the signal. The rise of the second shock was interrupted by the arrival of a relatively large amplitude signal, with a shape of approximately a phase-inverted *N*-wave. The overall signal was therefore considerably longer, lasting more than 0.3 s instead of 0.1 s. These large differences were due to the indoor complex propagation in the house, with transfer between rooms, multiple arrivals, wall reflections, diffraction or reverberation. Weak shock behaviour may also be different from the one of linear waves, as shown at least in the case of diffraction [51]. Spectrum oscillations observed in Figure 4 of [25] in the very low frequency part

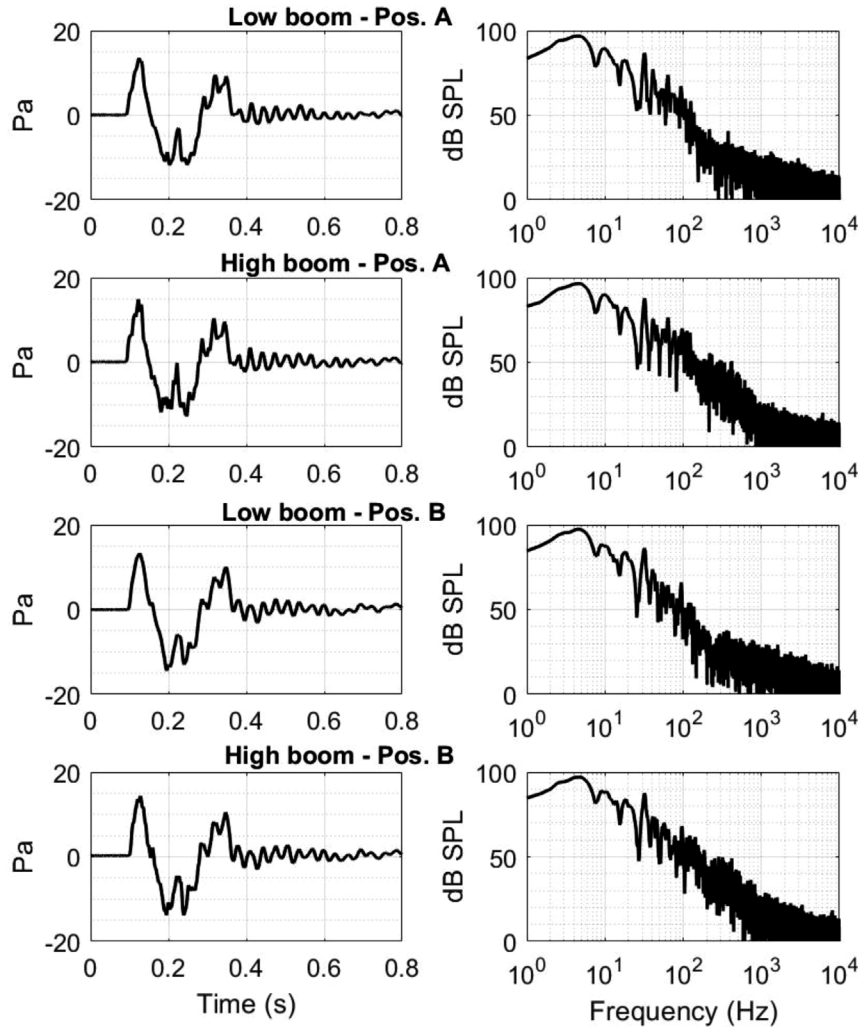


Figure A.1. Measured signals in the living room when operating the two simulators simultaneously, with an open kitchen door. Left column: time waveform – Right column: frequency spectrum. From top to bottom: Low Boom in position A – High Boom in position A – Low Boom in position B – High Boom in position B.

below the peak here disappeared. The wideband rattle noise from the kitchen affected the frequency spectrum above 800 Hz for the High Boom case, and above 200 Hz for the Low Boom case. Note that, when the kitchen door was closed, the peak overpressure in the living room increased because of a smaller insonified volume, but the sound level decreased because the higher frequency content due to rattle disappeared.

In the kitchen (Fig. A.2), the boom shape was once again different. The emitted N -wave shape was recovered, but followed by smooth, low frequency oscillations. The spectrum showed a secondary peak slightly below 10 Hz. This frequency was in agreement with the assumption of the volume of living room plus the two bedrooms (134 m^3) playing the role of a Helmholtz resonator, with the door between living room and kitchen (of surface 1.7 m^2 and of perimeter 5.94 m) being the resonator

aperture. With these values, the resonance frequency is estimated to be 10.4 Hz , close to the observed one. Such a resonance effect could also explain the small increase in boom peak overpressure in the kitchen (between 15.1 and 16.2 Pa) compared to the living room (between 13.3 and 14.8 Pa). The high frequency content showed an increase, of roughly 10 dB above 1 kHz , compared to the living room. As a counterpart, the frequency range 20 – 100 Hz was largely reduced compared to the living room. In terms of metrics, there was a clear reduction of High Boom levels in the kitchen (2 – 3 dB) compared to the living room, but not for the Low Boom levels. Levels at position D closest to the rattling door were always higher.

Rattle was evidenced by measuring the acceleration of the kitchen door to the garden. A single PCB Piezotronics accelerometer (model TLD333B40 – operating linearly up to $98 \text{ m} \cdot \text{s}^{-2}$ (peak) in the frequency range 0.5 – 3000 Hz)

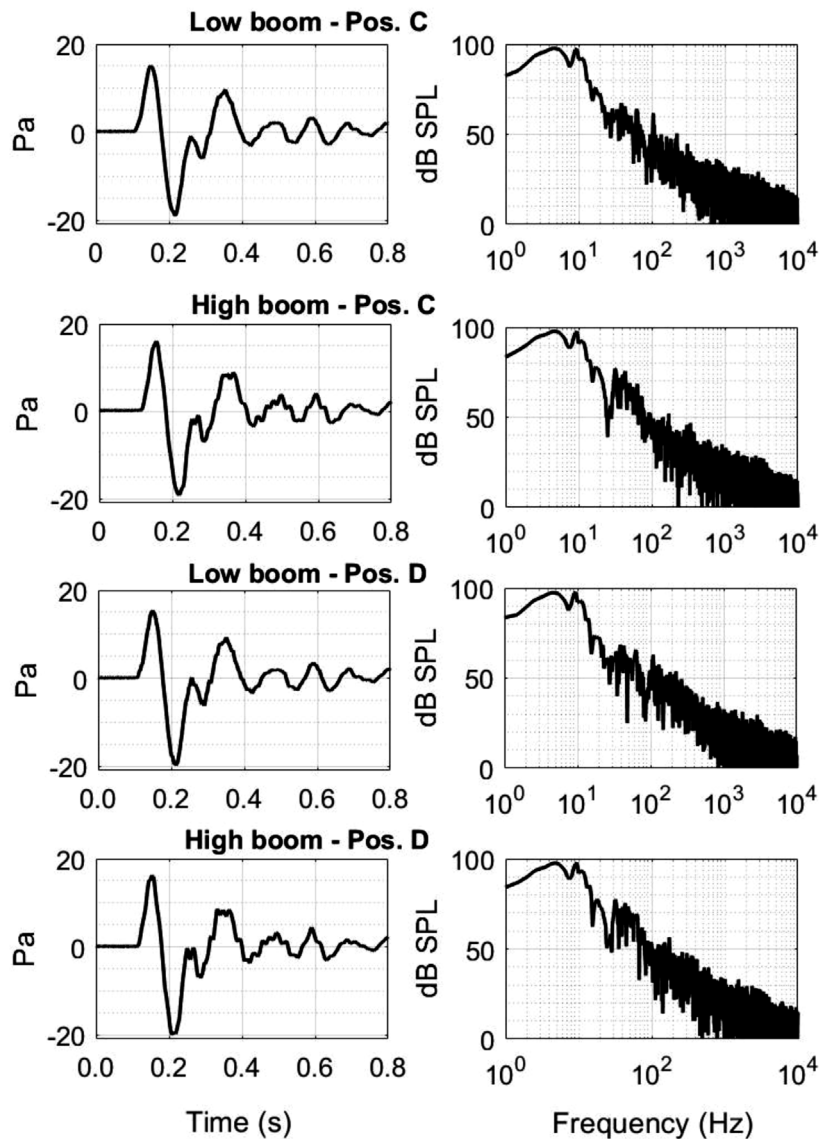


Figure A.2. Measured signals in the kitchen when operating the two simulators simultaneously. Left column: time waveform – Right column: frequency spectrum. From top to bottom: Low Boom in position C – High Boom in position C – Low Boom in position D – High Boom in position D.

was fixed by wax to the measured vibrating surface, its cable being always attached on a fixed surface to avoid any motion. It was connected directly to the same acquisition card NI USB 4431 as the microphones, which provided conditioning when used in IEPE mode. Measurements were made on both one of the door glass panes and on

the door wooden moving frame. Vibrations reached high levels, up to $60 \text{ m} \cdot \text{s}^{-2}$ for the High Boom. The acceleration signal showed several bursts corresponding to the moving door frame hitting the fixed one under the boom pressure wave. Wooden frames always showed larger accelerations than glass panels.

Appendix B

Summary of the statistical results

Motor control task	Number of spirals drawn	No statistical difference: 4.64 in average with a difference of less than 0.14 spirals between the conditions
	Time spent in the zone in which the boom appeared (compared to the neighbouring zones)	Significant effect: increase between 1.9% and 6.3%
Working memory task	Percentage of correct responses	No statistical difference: 87.3% in average with a difference of less than 7.2% between conditions
	Correct response time	Longer time (by 3.9%) for card #0 and #1 compared to the four cards preceding the boom, longer (by 3.4%) for the Low Boom condition compared to the High Boom condition and longer (by about 4.3%) in the living room compared to the kitchen
Communication task	Communication efficiency	Compared to the no boom condition, efficiency impaired by 14.7% in the Low Boom condition and by 4.8% in the High Boom condition, though below statistical significance in both cases
Valence evaluation task	Percentage of correct responses	More correct responses when primes were booms than when they were not (2.3% increase for Low Booms, 1.1% increase for High Booms)
	Correct response time	Longer time when primes were booms than when they were not (4.2% increase for Low Booms, 3.8% increase for High Booms).

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