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A child-centred experiment to test an individually controlled noise-reducing device

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ABSTRACT

A recently published simulation-based study has demonstrated the effect of an individually controlled noise-reducing device (ICND) on improving acoustic quality in classrooms. As a follow-up research, this current study aims to develop a real ICND and test it with its target users-- primary school children. The prototype developed in this study looks like a canopy hanging above a desk, was selected and prototyped. It has two modes, i.e. open and closed, and can be easily changed by a remote controller. With this device, school children can control their local acoustic environment by themselves. More than 200 primary school children have been invited to test two prototypes of this device in the acoustical chamber of the SenseLab. The results showed that 83% of the children liked this device and 61% of them wanted to have it in their own classroom. However, since this is a prototype, there is still room for improvement. Based on the children's feedback, several suggestions for future modifications have been summarized.

1. Introduction

In recent decades, noise perceived in classrooms of primary schools has drawn worldwide attention. According to an investigation conducted among 1145 Dutch primary school children, noise was reported to be the biggest indoor environmental problem in primary school classrooms [1], and the sound generated from children themselves and their classmates was described to be the main noise source [1–3]. Poor acoustics in classrooms has also been observed in Brazil, where the teachers and children reported noise created in their neighbouring classrooms as the main source of annoyance [4]. Also, in the United States, the inferior acoustics in classrooms is a common problem. Seep et al. [5] found that the speech intelligibility rating in many American classrooms was 75% or less due to excessive noise, which means that students with normal hearing on average missed one word among every four spoken words in these classrooms.

Apart from the research on perceived sound, many studies have been conducted including objective acoustic measurements in classrooms [4,6,7]. Unfortunately, the measured acoustical quality in most studies rarely reached the standards set for primary schools around the world. For example, in a study conducted in 26 classrooms of seven schools in Medellin, Colombia, none of these classrooms met the related acoustic requirements [8]. A survey of acoustic conditions of unoccupied classrooms in Canada demonstrated that even in most of the newly renovated classrooms, the background noise level and reverberation time (RT) could not meet the standard [9]; and in the United States, a study on the acoustics of classrooms showed that the ambient noise level in only one among the 16 tested classrooms met the national standard [10].

Since hearing and understanding verbal information is important for a good learning process, many researchers began to pay attention to the observed poor acoustics of classrooms. Therefore, the impact of poor acoustics on school children have been well studied [11–14]. An experimental investigation conducted by Valente et al. showed that excessive noise and a too long reverberation time could impair speech intelligibility and, therefore, has a negative effect on children's learning performance [15]. Similar results have been found by Klatte et al. [11], who identified the relationship between perceived noise in classrooms and children's poor performance in verbal tasks. They demonstrated that the long-term exposure to noise may have adverse impact on children's cognitive development. Moreover, in primary schools, the speech perception of younger children is more affected by noise than with older children [16].

Considering the poor acoustics in classrooms and its impact on school children, it is urgent and important to find a way to reduce noise that improves the acoustical quality of classrooms. To do so, in the past decades, many schools have been renovated by adding sound absorption ceiling (and/or wall) panels. As a common

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acoustic-improving method, adding acoustic panels demonstrated to be useful in some studies [17–19]. However, in recent studies this conventional method showed to be not effective enough. In a study of the renovation of a children's playground, Chmelik et al. concluded that the influence of roof materials on the sound pressure level (SPL) around the playground area was very low [20]. Also, in a field study conducted in 21 primary schools in the Netherlands, the children were bothered by noise even though almost all of the investigated classrooms had sound absorbing ceilings [1]. For those classrooms it can be concluded that a more effective noise-reducing solution is needed.

The acoustics of a classroom is difficult to assess by simply using average values for the whole classroom because there is much variation in children's sound perceptions and speech intelligibility scores under the same acoustical conditions [12,16,21]. Therefore, it makes more sense to assess the acoustics individually. Additionally, Zhang et al. [22] also found that children are different from each other in terms of their IEQ needs and preferences, some being more sensitive to noise than others. Thus, they suggested to apply individually controlled devices for each child to improve the learning environment. A recent simulation-based study conducted by the same team, proved an individually controlled noise-reducing device (ICND) to be a better solution than an absorbing ceiling [23]. The simulation results indicated that compared with the traditional acoustic improvement (ceiling tiles), the ICNDs could provide a shorter RT and higher speech intelligibility in a classroom for the same amount of added sound absorption. Therefore, as follow-up research, the present study designed and prototyped such an ICND for primary school children and focused more on children's experience and feedback on this device.

2. Method

In general, this study consists of two steps: the designing and testing of the ICND. For the first step, the design process of the ICND was introduced; for the second step, a subjective test (with children) by means of a user-centred experiment was carried out to test the usability of this device.

2.1. Design of the ICND

As a complete and typical product development process, four steps have been involved in the ICND development: customer need (or market opportunity) analysis, concept development, functionality modelling, and product design (see Fig. 1) [24]. Detailed information on the first three steps can be found in previous papers [1,23,25]. The current paper only focusses on the last step: design of the ICND. According to previous studies, to design a well-functioning product, a good design team should be built up at first [26]. Therefore, a ICND design team, including a profession in indoor environment, a professor in industrial design, an acoustic expert, a technologist, and a PhD student, was organized. After the first several brainstorms, three simple models of design alternatives were made manually (see Fig. 2). Then, as suggested by the Interaction Design Foundation [27], these three models were compared and discussed within the design team to collect simple and rough feedback. Since the target users are school children, the safety and durability of the device came out as the main concerns. To avoid hindering children's daily activities, it was decided to install the devices on the ceiling above every child's head. After the discussions among the team members, the final version of the ICND was designed and prototyped.

As shown in Fig. 3, the final version of the ICND consisted of one main (fixed, horizontal) panel and six (movable) side panels, all comprised of one MDF (medium-density fibreboard) inner layer and two outer layers of acoustic foam with an average thickness of 30 mm and a total geometric area of 0.70 m^2. The main panel is a hexagon, and each side panel consists of two trapezoids connected under an angle of 171° (see Fig. 3). These sizes were based on the real size of education furniture in the Netherlands. These six side panels were connected to a linear motor (the blue part on top of the hexagon in Fig. 3) with steel cables (the blue lines in Fig. 3), and to make the cables move smoothly, six wheels were placed at the middle of each edge of the main panel. The whole prototype weighs around 2 kg. As shown in Fig. 3, it has two modes: open (Fig. 3 b) and closed (Fig. 3 a), which can be changed easily using a remote controller with two push buttons. The idea is that the modes can only be changed during the self-study or group discussion time, while during the teaching time all the devices should be open so that all the children can see the blackboard and interact with the teacher. The depth of the closed ICND, namely the vertical distance between the edge of the main panel and the edge of the side panels, was 163 mm. A short manual for the use of the remote controller was placed on top of the desk during the test. The cost of making this prototype was around 80 Euros.

2.2. Test of the ICND

The experiment was carried out during Dutch school holidays between the 20th of August and the 27th of October, in the acoustics chamber of the SenseLab [28] located in the Science Centre Delft, The Netherlands. In total, there were 25 test days, including 8 days during the summer holidays, 8 days during weekends, and 9 days during the autumn holidays. More than 300 visitors, including children and adults, participated in the experiment and 274 of them completed the questionnaire. All participants were normal visitors of the Science Centre Delft and their involvement in this experiment was on a voluntary basis. As one of the normal programmes of the Science Centre, this experiment was conducted during three sequences on a test day, each of which lasted around 40 min: 12:00–12:40, 14:00–14:40 and 16:00–16:40.

2.2.1. Questionnaire design

According to global children's development stages and Piaget's theory of the four stages of cognitive growth, children aged 7 to 12 (which are the target users of this device) are in the "concrete operational stage" and their cognition becomes relatively mature and "adult like", therefore, they are eligible to be surveyed by questionnaires [29,30]. However, special attention still needs to be paid to designing the questionnaire for this group of children. For example, the length of the questionnaire and the words used in the questionnaire should be carefully considered since their comprehensive and communicative abilities are still developing. According to previous studies with school children [29,31,32], the questions should be short and easy to understand. Furthermore, the "I like, I wish, What if" questions are suggested to be used to collect honest feedback and the response options are preferably limited to three or four. Based on these suggestions, the questionnaire was designed. And after a small pilot test, the final version was confirmed.

The questionnaire contained three parts: a brief introduction, 5 questions about personal information and 9 questions about feedback on the ICND (including the demand, function and usability of this device; see Appendix A). The introduction ended with a short permission letter to ask the parents' permission to allow their child to take part in the test. To make the questions easier to understand for children, several icons were added to some questions (see Fig. 4).

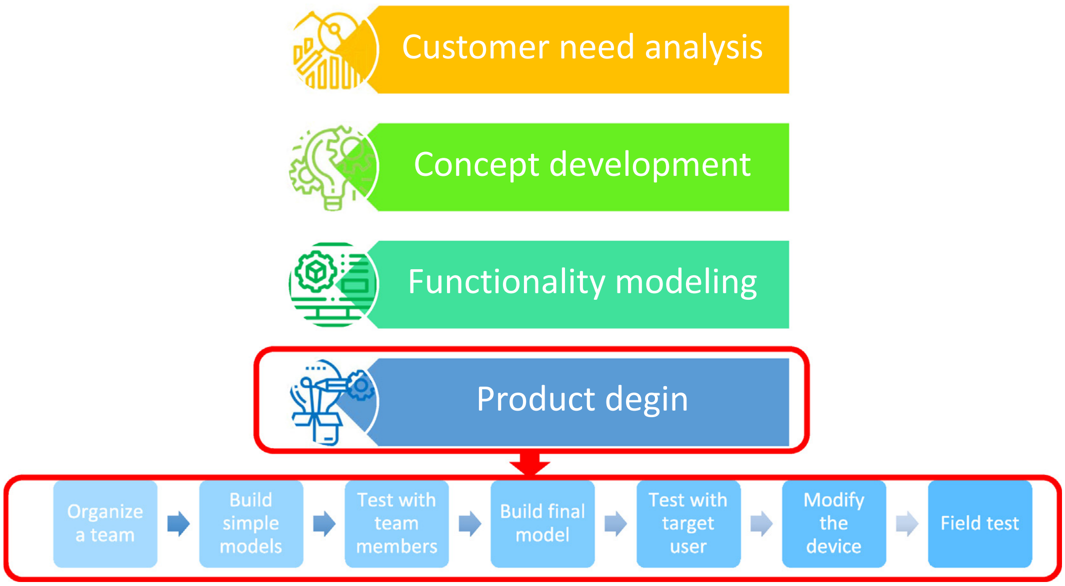


Fig. 1. Procedure of design the ICND.

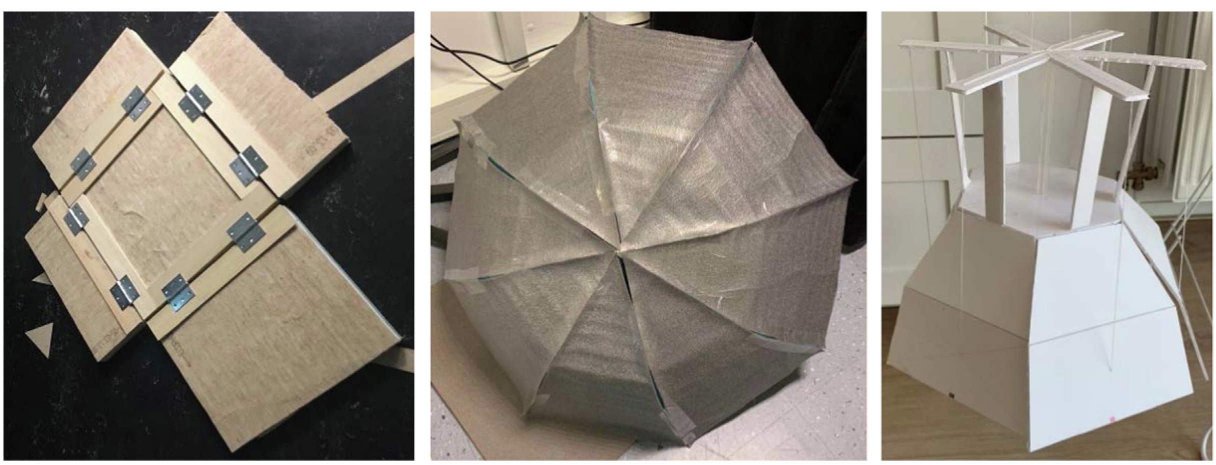


Fig. 2. The previous versions of the ICND.

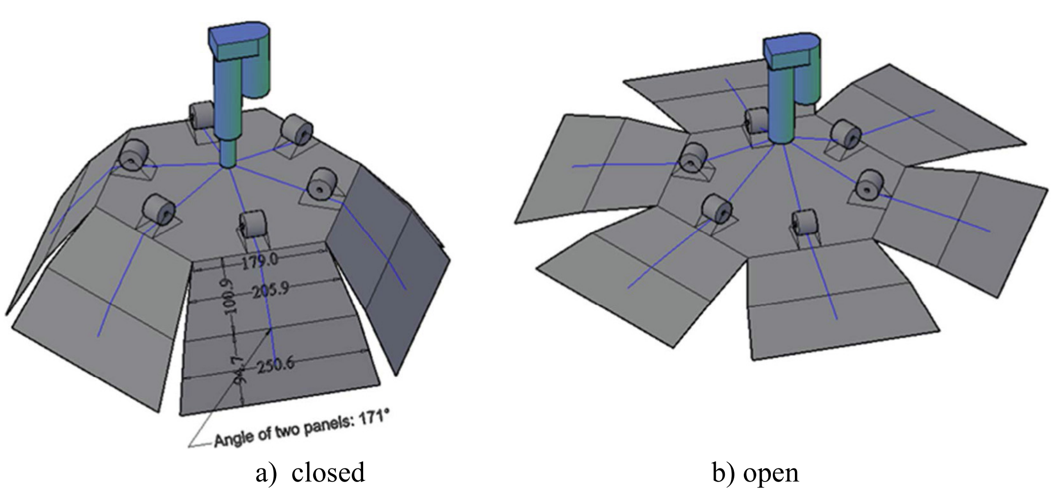
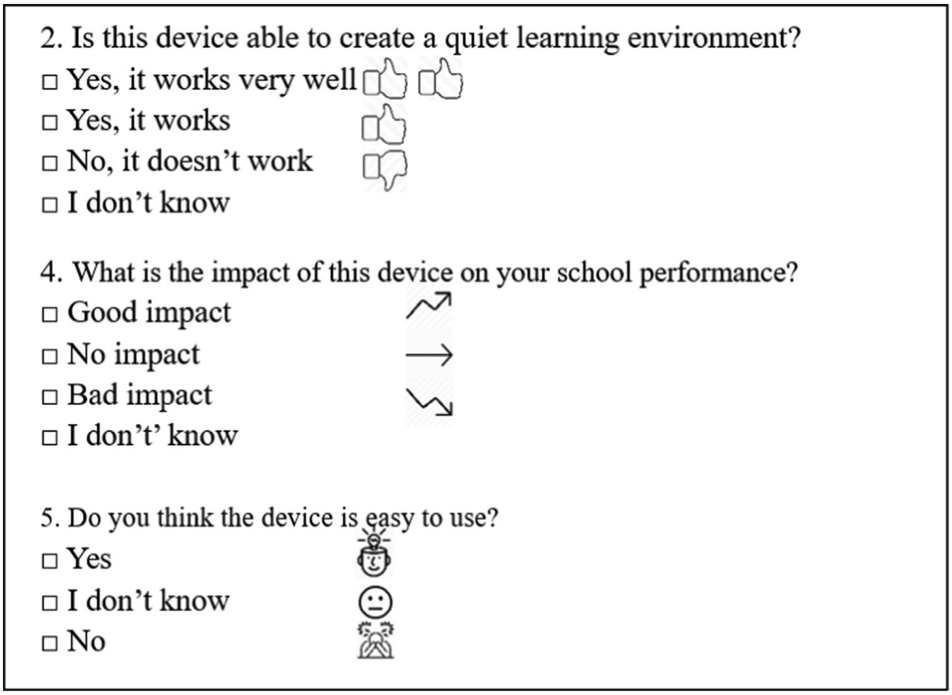


Fig. 3. The schematic diagram of the final version of the ICND.


2. Is this device able to create a quiet learning environment?
□ Yes, it works very well
□ Yes, it works
□ No, it doesn't work
□ I don't know

4. What is the impact of this device on your school performance?
□ Good impact
□ No impact
□ Bad impact
□ I don't't' know

5. Do you think the device is easy to use?
□ Yes
□ I don't know
□ No

Fig. 4. Examples of icons added to the questionnaire to increase understandability.

2.2.2. Test chamber setup

The acoustics test chamber is a rectangular room a fully reflective room (RT = 0.4 s) with the dimension of circa 2.5 m (l) × 2.3 m (w) × 2.1 m (h).Since this is a very small chamber, the direct sound generally is dominant over the reverberant field. In this chamber, two identical ICNDs were installed above two sets of school desks and chairs, at the height of 1.8 m above the floor (see Fig. 5). The ICNDs could be controlled by a remote controller with three buttons, corresponding to "open", "closed" and "pause" (which was not used in this experiment). During the experiment, children could open or close the device by pressing one of these buttons. Moreover, as can be seen in Fig. 5, on the back wall, two information letters (one in Dutch; one in English) and two posters (one in Dutch; one in English) explained the reasons for the design of this device and showed the safety instructions (e.g., do not touch the device). This information helped participants to better understand and complete the experiment.

Fig. 5. The layout in the test chamber.

2.2.3. Test procedure

Before participants came into the test chamber, a researcher first introduced them to the purpose of the experiment and its procedure, and then gave them a double-sided, one-page questionnaire and a remote controller. Two children could test the ICNDs at the same time. During the testing time, children had around 4 min to experience the device and were free to talk with each other, created noise, and could open or close the device at any time. No extra artificial noise was played during the test, all the noise was generated through their neighbour's talking, moving chairs, and clicking pens, because these types of noise were the main annoyances for the children in Dutch primary schools [1]. After this experience, they were given another 3 min to complete the questionnaire. On average, the whole procedure took around 7 min. During the test, at least one researcher waited outside the chamber, so that the participants could ask questions whenever necessary. Additionally, since this was a voluntary experiment, participants could skip any questions or even leave the chamber at any moment.

2.2.4. Data analysis

All data from the questionnaires were manually typed and stored into a digital database, and then analysed using SPSS version 23.0 (SPSS Inc. Chicago, IL, USA). Three data analysis methods were used in this study, namely descriptive analysis, relationship analysis and content analysis. First, all general information of the participants, such as their age and gender, were analysed using descriptive analysis. Additionally, this analysis was also applied to all the device-related questions to get a general understanding of the children's opinion on this device. Next, to identify the reason why children liked or wanted to have this device, a Chi-squared test was used to analyse the relationships between these two questions and the five previous questions that were about the usability and functionality of the device. Lastly, content analysis was used to sort out children's various answers on three open questions, i.e. the reason why they liked/disliked the device, the reason why the device was wanted/not wanted, and their suggestions for improvement. Before this analysis, all the children's written answers were coded into several different categories based on keywords and main ideas.

2.2.5. Ethical aspects

Before the experiment, all the parents or supervisors of the participating children were asked for their consent by signing an approval form. Moreover, the participants could skip any question or step out of the experiment at any time if they wanted. The Ethics committee of the TU Delft gave approval for the study.

3. Results

3.1. Participants

In total, 274 random, normal visitors from all over the country participated in the survey during the 25 test days (convenience sample). Among them, the participants whose age was not between 5 and 13 (Dutch primary school children age range) and/or who had a hearing problem were excluded from the analysis. After the filtering, 209 children were left, and 201 (96%) of them, including 95 girls and 106 boys, were considered as the valid participants because they completed more than half of the questions. The average age of these participants was 9.5 (SD 1.9) years old.

3.2. Descriptive analysis

Children's feedback on the device was collected by asking them questions such as: "Is this device able to create a quiet learning environment?", "What is the impact of this device on your school performance?", "Do you think this device is easy to use?" (see Table 1). For the first three questions, all the affirmative answers were combined - for example, "yes, it works" and "yes, it works very well" were combined as "yes, it works" -, while all the other answers were kept in their original version. All the device-related questions were classified into three categories: questions 2,4, and 5 were about the functionality and usability of the device; questions 6 and 7 were about the overall impression of the device; and question 8 was about the imaginary user behaviour. The results of the descriptive analysis, except for the open questions, are shown in Table 1. For questions 1–5, the values in parentheses show the results excluding the answer "I do not know".

In general, all the answers were quite positive. For the overall impression, 83% of the participants liked this device and 61% of them wanted to have one in their classroom. With respect to the acoustical quality in their classrooms, 76% of the children thought it was necessary to reduce noise and 49% (70%, excluding "I do not know" answers) thought this device could create a quiet learning environment. Concerning their performance evaluation, 75% of the participants thought reducing noise could benefit their school performance and 36% (64%, excluding "I do not know" answers) of them thought this device would have a good impact on their performance. And in terms of the usability, 82% (94%, excluding "I do not know" answers) thought this device was easy to use, and if they had one, 56% would change its mode several times a day.

3.3. Relationship analysis

Considering that questions 1–5 were about the functionality and usability of the device, which could be regarded as the reasons for why the participants liked or wanted to have the device (questions 6 and 7), it is interesting to test whether there is a relationship between them. Table 2 shows the results of the chi-squared analysis between questions 1–5 and questions 6–7. There are statistically significant relationships between these questions, except for the relationship between "It is necessary to reduce noise in classrooms" and "I like the device". Moreover, the standardized residuals showed that children who liked the device somewhat more frequently, were of the opinion that "reducing noise contributes to good performance", "this device is able to create a quiet learning environment and is easy to use", and "it will have a good impact on performance". Similarly, the standardized residuals also showed that children who wanted to have this device more

Table 1
Results of the descriptive analysis.

Questions	%
1. Is it necessary to reduce noise in classrooms?	
- Yes, it is necessary	75.6 (86.4)
- No, it is not necessary	11.9 (13.6)
- I do not know	12.4
2. Is this device able to create a quiet learning environment?	
- Yes, it is	49.4 (70.4)
- No, it is not	20.7 (29.6)
- I do not know	29.9
3. Will reduction of noise help you with your school performance?	
- Yes, it will	75.0 (91.5)
- No, it will not	7.0 (8.5)
- I do not know	18.0
4. What will the impact of this device be on your school performance?	
- Good impact	35.5 (64.1)
- No impact	15.1 (27.2)
- Bad impact	4.8 (8.7)
- I do not know	44.6
5. Do you think the device is easy to use?	
- Yes	81.9 (94.2)
- No	5.0 (5.8)
- I do not know	13.1
6. Do you like the device?	
- Yes	82.8
- No	17.2
7. Would you like to have one in your classroom?	
- Yes	61.338.7
- No	
8. If you have one in your classroom, how often will you change its mode?	
- Several times a day	55.6
- Once or twice per day	21.2
- Less than once a day	3.2
- Almost never	20.1

Note: the numbers in the parentheses mean the results obtained excluding "I do not know".

Table 2
Result of the Chi-squared analysis between the questions.

	I like the device. χ^2 (p)	I want to have one in classrooms. χ^2 (p)
It is necessary to reduce noise in classrooms.	1.60 (0.659)	17.17 (**0.001**)
This device is able to create a quiet learning environment.	24.18 (**<0.001**)	29.02 (**<0.001**)
Reducing noise contributes to good school performance.	21.68 (**<0.001**)	21.76 (**<0.001**)
The device will have a good impact on school performance.	11.80 (**0.008**)	31.50 (**<0.001**)
This device is easy to use.	37.81 (**<0.001**)	30.73 (**<0.001**)

frequently, found that "it's necessary to reduce noise in classrooms", "reducing noise contributes to good performance", "this device is able to create a quiet environment and is easy to use", and "it will have a good impact on performance".

Furthermore, this study also analysed the relationship between whether the participants liked the device and whether they wanted to have it. The results showed that a statistically significant relationship did exist between these questions ($\chi^2(2) = 26.95$, $p < 0.001$). The standardized residuals indicated that the participants who liked the device inclined to want to have it in their classroom. This relationship did make sense: usually when one likes something, one is more eager to want it, and to some extent, the existence of this relationship between these questions might imply the reliability and logicality of children's answers.

3.4. Content analysis

To further understand the children's opinion on this device, this study used content analysis to qualify the presence, meaning and relationships of the children's answers to the three open questions. For each question, several short sentences summarized the children's original answers. Next, these sentences were classified into three categories (appearance, functionality, and usability) complying with the three emphases that users have when they buy products [33]. Six experienced researchers were individually asked to group all these sentences into the three categories and the most frequent categorisation was further used in this study. The inter-rater reliability was checked using the kappa score, which was higher than 0.4 [34], indicating a strong agreement among these researchers. Based on that outcome, the classifications presented in this paper could be considered reliable.

3.4.1. Open question 1: Why do/don't you like this device?

In total, 124 out of 164 children who liked this device and 21 out of 34 children who did not like this device wrote down the legible reason why they had such an impression. For those who liked it, two, four, and two subcategories were identified under the categories of appearance, usability and functionality. While for those who didn't like it, only one subcategory under each category was identified (see Fig. 6).

Fig. 6 indicates that the reason why many children liked this device was almost evenly distributed into these three categories, with appearance as a slightly more important reason. While the reason why some children disliked it, was mainly because of its insufficient expected functioning.

3.4.2. Open question 2: Why do/don't you want to have this device in your classroom?

For this question, 82 out of 117 children who wanted to have this device and 51 out of 74 children who didn't want to have the device gave their clear reasons. According to the content of their answers, the subcategories were classified and presented in Fig. 7.

It is interesting to see that the reason why children wanted to have this device was mainly because of its expected functioning. Most of the children who wanted to have it thought it worked/ helped/ reduced noise. Likewise, functionality was also the main reason why some children did not want to have it. So, functionality seems to be the key factor for children to decide whether they want to have this device or not.

3.4.3. Open question 3: How do you want to improve this device?

With respect to suggestions for improvement, 121 children expressed their ideas clearly, and 10 of them mentioned more than one idea. Therefore, 131 ideas were collected, and according to the content of these ideas, the subcategories were classified and presented in Fig. 8. As can be seen, the children's suggestions were mainly focused on the usability. Most of the children wanted to make it lower and closer to their ears. Furthermore, many children reported that they preferred the linear motor to make less noise.

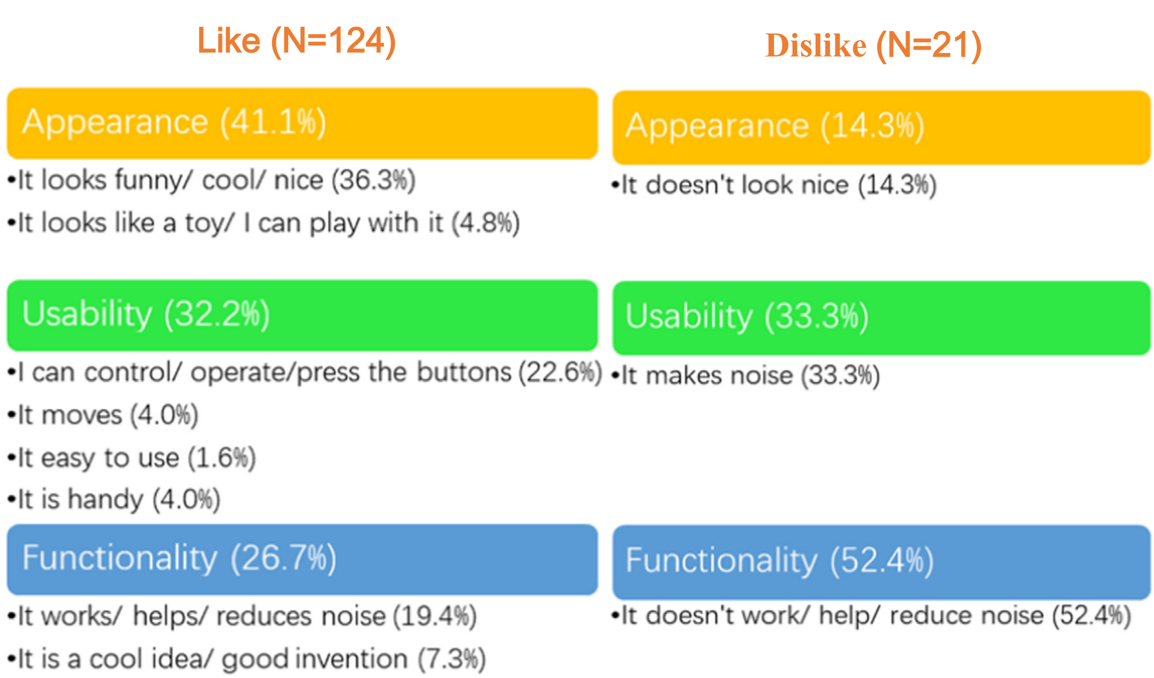


Fig. 6. The classification of subcategories based on the "like/dislike" question.

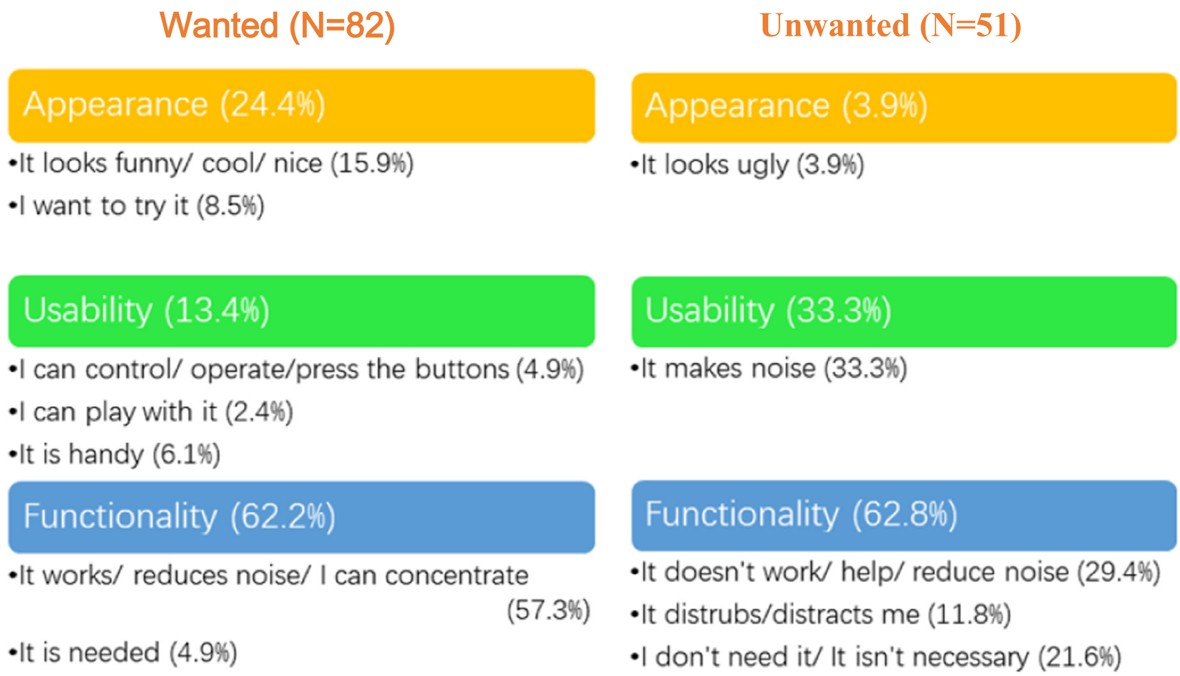


Fig. 7. The classification of subcategories based on the "wanted/unwanted" question.

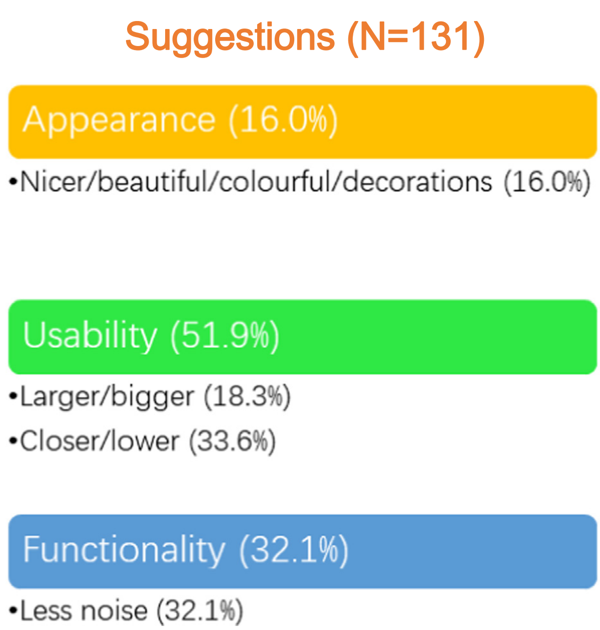


Fig. 8. The classification of subcategories based on the "improvement suggestions".

4. Discussion

4.1. Acoustic problem in classrooms

The analysis results of the questions related to the acoustics in classrooms revealed a poor acoustical quality in Dutch primary schools: 76% of the children thought it necessary to reduce the noise in their classrooms and 75% thought they would have a better performance if their learning environment was quieter. This confirms the results reported by a previous field study which showed that most children were bothered by noise in their classrooms and reported that "hearing teacher" and "indoor sounds" were two important factors that could have an impact on their performance [22]. Even though many classrooms did have absorbing ceiling panels, the acoustics still seemed not good enough to provide a quiet learning environment [1]. The study reported here confirmed the importance of the need of providing more effective acoustic treatment.

4.2. Feedback from children

201 completed questionnaires were analysed. The relationships between the answers to different questions implied that the children's answers were consistent and reliable [35]. Generally speaking, their feedback on the ICNDs was positive, most of them liking it and wanting to have one in their classroom. The relationship between these two questions and other questions indicated that the reason why children liked the device and wanted to have it, is that they believed this device is able to reduce noise and therefore will have a good impact on their school performance. Furthermore, the content analysis of the open questions studied the direct reasons of the children's preference. They liked this device mainly because it looked funny/cool, and they wanted to have it mainly because it worked/helped/reduced noise. In terms of the negative feedback, the reason why some children did not like the device or did not want to have it was mainly because they thought this device did not work for them or because this device itself also made noise. Indeed, the linear motor of this device made noise when it moved, which is contrary to its design purpose for reducing noise. Therefore, this might be the reason why many children suggested to reduce the noise created by the device.

4.3. Application potential of ICNDs in real classrooms

In the simulation study, Zhang et al. [23] have compared the function of ICNDs with not only the control situation (where no acoustic improvement was implemented) but also the traditional acoustic improving method used in classrooms, namely installing ceiling panels. The simulation results showed that compared with ceiling panels, ICNDs could lead to a shorter RT in both self-study (with closed ICNDs) and instruction (with open ICNDs) situations, and a lower the SPL of talking children in the self-study situation and a higher SPL of the teacher's voice in the instruction situation. These results provided the theoretical basis of applying ICNDs in classrooms. Additionally, in the underlying study a prototype was built and tested with school children. The positive responses from the participating children further demonstrated the application potential of the ICNDs. However, the limited size of the test chamber affected the performance of the ICNDs, because the distance between the sound source and receiver was quite small, and the direct sound was dominant in this situation. In that case, the difference caused by changing the modes of the devices could hardly be noticed. However, real classrooms are much larger than the test chamber and the distance between the sound source and receiver will most likely be larger than the reverberation radius. Therefore, the reverberant field will be dominant in the real classrooms, and in this context, the ICNDs are expected to work more effectively and have a bigger effect.

4.4. Possible improvement of the current device

According to the children's feedback in this study and the results reported in the previous study [23], an ICND may be a possible solution for children to control their individual acoustical environment. However, in this study it was seen that there are still some problems with the device designed and tested, such as the noise produced by the linear motor during operation and its boring appearance. The suggested improvements by the children were mainly focused on reducing this noise and changing its height. Many children suggested to lower the height of the device. However, a too low height might cause accidents, such as children bumping their heads against it. Therefore, a better solution might be to change the moving pattern from open/closed to up/down. There are several possibilities to do this, for example, by changing the motor or using a mechanical method (e.g. a rope), which could also reduce the noise created by the device. All these possible improvements might be put into practice in future studies. Apart from the children's suggestions, the noise-reducing effect of this device could also be further improved by increasing the thickness of the acoustical foam layers. The next version of this device can also be combined with an additional lighting system and/or even a personal ventilation system, so that the whole local environmental quality can be controlled and improved personally.

4.5. Limitations and future studies

Several potential limitations can be put forward. The first one is about the size of the test chamber. Since the dimension of the test chamber is different from a typical classroom, the function of ICNDs and children's feedback on them might differ in real classrooms. Another limitation concerns the evaluation method. The main method used in this study was self-reported questionnaire, which is quite subjective, children might not be able to assess the device accurately. These limitations suggest that future studies should test the device in a real classroom with school children, so that the actual performance of the devices can be tested.

5. Conclusion

In this study an individually controlled noise-reducing device (ICND) was designed and tested with more than 200 school children. Based on the outcome, it can be concluded that this ICND was very welcomed by the school children. They reported that the device would likely reduce noise and make them concentrate better. Because there is still room for further improvement, new versions should be designed and developed, and further tests need to be performed with school children in the future. Still, this study demonstrated the potential of a hanging open/closed ICND to reduce noise produced by talking children in classrooms.

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CRediT authorship contribution statement

Dadi Zhang: Formal analysis, Methodology, Writing - original draft. **Martin Tenpierik:** Writing - review & editing, Supervision. **Philomena M. Bluyssen:** Writing - review & editing, Supervision.

Declaration of Competing Interest

The 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. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apacoust.2021.108373.

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