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Discover Education

Brief Communication

A peer instruction based board game to teach quantum technologies to engineers

Deborah E. Carberry[1] · Jonas S. Neergaard-Nielsen[2] · Evert Van Nieuwenburg[3] · Martin P. Andersson[4]

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Abstract

In this study, we develop and test a board game to introduce quantum computing to engineering students. The instructional approach is informed by peer instruction and flow theory. To begin, Bloom's taxonomy is leveraged to profile the intended learning outcomes (ILO's) from a master's course in Quantum Information. This is followed by a filtering exercise to shortlist the ILO's that are deemed suitable for our intended audience and for use in a boardgame. Design thinking informs the design methodology. The game, *States & Gates*, is differentiated from other similar offerings in that it is designed specifically for a technical audience where, for example, it leverages matrix multiplication as a game mechanic. For product testing, a feedback form is used to evaluate the design and instructional value of the product. The goal is to identify from what/whom the players learn, alongside questions about perceived aesthetics, usability and sentiment. The feedback suggests that peer instruction is a critical pedagogic aspect of playing the game, and that this form of instruction is most effective for players who identify as being novice, but not entirely new to the subject. Further, several suggestions for product improvement were offered that warrant the development of augmented digital features. The game was developed as a tool for the community and is available for download at our GitHub repository.

Keywords Quantum computing · Engineering education · Peer instruction · Flow theory · Game-based learning

1 Introduction

1.1 Background

This paper presents an instructional design project to develop methods for educating (chemical) Engineering students about Quantum Computing. Given the current rate and trajectory of technological innovation, it is increasingly difficult for educators to maintain their role as experts in all the technologies that pertain to their respective fields. Further, we must also be aware of the likelihood that the current state of the art will be short lived and replaced with increasingly sophisticated and potentially more complicated alternatives. Thus, in a culture of expert-novice education paradigms, and without subject matter experts, the capacity of higher education to deliver a learning curriculum that continually

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✉ Deborah E. Carberry, debca@kt.dtu.dk; ✉ Martin P. Andersson, martin.andersson@kfupm.edu.sa | [1]Department of Chemical and Biochemical Engineering, Technical University of Denmark, Lyngby, Denmark. [2]Department of Physics, Technical University of Denmark, Lyngby, Denmark. [3]Leiden Institute of Physics, Leiden University, Leiden, Netherlands. [4]Center for Integrative Petroleum Research, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia.

matches emerging occupational profiles is limited. However, productized learning, coupled with peer instruction and mentorship, may offer a viable solution. Here, boardgames can be a suitable medium for facilitating peer instruction and other teaching discourses that are contrary to expert-novice models of teaching and learning. In this paper, we will present a project to develop a boardgame that is intended to introduce higher education engineering students to the subject of quantum circuits, a key concept in utilizing the future power of quantum computing in engineering applications. The boardgame takes inspiration from a Masters course 'Quantum Information' offered by the Physics department at The Technical University of Denmark (hereafter referred to as DTU) [1]. In particular, one intended learning outcome of this course, '*Explain the main concepts of quantum computing, including gates, circuits, and error correction*', was identified as being both appropriate for an undergraduate engineering audience whilst also being suitable for productization (Table 2). The paper will commence by filtering specific learning objectives from the course and mapping them to learning objectives for a boardgame. Thereafter, using Design Thinking as a framework, several features of the game will be illustrated. Finally, the outcomes of a play test session that was undertaken as part of a Quantum Computing workshop at the Chemical & Biochemical Engineering department at DTU will be presented. Titled '*States & Gates*', the corresponding boardgame is offered to the community as a tool for their own classrooms. The board game is subject to a creative commons license and users are invited to test, alter, improve and extend the game as they see fit.

1.2 State of the art

Several quantum-based boardgames exist in the literature. More than half of these leverage popular games such as Jumanji [2], Snakes and Ladders [3], Go [4] and Tic-Tac-Toe [5] as the foundation for their gameplay. In other instances, an original game is devised. Not surprisingly, the papers we reviewed that presented original game designs described similar design approaches to our own [6, 7]. For this reason, we prioritized these original games for a comparative analysis. Notwithstanding, we included one classically inspired game, Tic-Tac-Toe.

Introducing each of these games in turn; *Quantum Race* [6] uses the world of a racetrack to introduce several quantum effects such as tunnelling and teleportation. *Entanglion* [7] uses interplanetary spaceships to approach the topics of entanglement and error. *Quantum Tic-tac-toe* [5] uses X's and O's in a 3*3 grid to express a vast range of quantum metaphors. Finally, our game *States and Gates* uses a Bloch sphere to teach players how to perform unitary operations.

Comparing the topics listed across these four games (Table 1), we establish that all games address quantum states and superposition, whilst most address qubits and quantum gates. Beyond these topics, the focus of the respective games begin to diverge.

Generally, *States and Gates* has a narrower and more literal focus than the other games. It introduces its players to the symbols and notation of quantum mechanics and employs mathematics, matrix multiplication specifically, in the gameplay. As we shall see later, the symbols and notation form part of the visual landscape of the game and facilitate 'moving', whilst matrix multiplication is exploited as a game mechanic. These features that are unique to *States and Gates* are not ideal for a non-technical audience, nor are they intended to be. Since the goal of this project is to develop tools to introduce quantum computing to Engineering students and professionals, we find it quite fitting that what sets *States & Gates* apart from other offerings is that its playability relies on prior technical learning.

1.3 Education theories

1.3.1 Bloom's taxonomy

The taxonomy of educational objectives, more commonly referred to as Bloom's taxonomy, was first published in 1956 [9] and updated in 2001. The original purpose of the taxonomy was to classify educational goals. As a general concept, it can be appreciated that all of the education objectives listed in the taxonomy, i.e. remember, understand, apply, analyze, evaluate and create, can be designed for by using gameboards as a teaching modality. It follows then that leveraging boardgames as teaching tools can support good pedagogic design. Bloom's taxonomy is relevant to this study because it can be used to illustrate the cognitive investment required for learning, subject to the corresponding teaching modality.

Table 1 Comparative Analysis: Topics addressed for specific quantum-related & game-based-learning boardgames

	States & gates	Quantum race	Entanglion	Quantum Tic-Tac-Toe
Audience	3rd Level Students	Secondary Students	Students	Students
	Professionals	Adults	Enthusiasts of all Ages	
Topics				
Qubits	✓	✓	✓	
Quantum States	✓	✓	✓	✓
Quantum Gates	✓	✓	✓	
Superposition	✓	✓	✓	✓
Entanglement		✓	✓	✓
Evolution	✓			✓
Measurement		✓	✓	✓
Errors		✓	✓	
delocalization		✓		✓
De-coherence		✓		✓
Tunnel effect		✓		
Quantum teleportation		✓		
Symbols & Notation	✓			
Mathematics	✓			
Hardware Components			✓	
Software Components			✓	

1.3.2 Flow theory

Flow theory [10] defines a state of mind whereby one becomes entirely immersed in an activity. It is an important theory, for instructional and game design, where it is beneficial to match the challenge of the activity with the skill level required to complete the same activity. According to Csikszentmihalyi's flow model, if the challenge is too easy, apathy or boredom may set in. Conversely, if the challenge is too difficult, worry or anxiety may arise. The goal of good design, therefore, is to design an experience that is difficult enough to stretch, but not overwhelm, the learner. Early in the design phase of this study, we were confronted with the problem of how to maintain active participation in the game among players who were new to the subject of quantum mechanics. Flow theory was important in this regard and supported the design of game mechanics that facilitated engagement for all levels of knowledge and skills.

1.3.3 Peer instruction

Peer instruction is, by a simple definition, a teaching approach where students teach each other. Methods have been developed by Peter Mazur with a view to improving the conceptual understanding of topics among science-based students [11, 12]. Owing to its active nature, Mazur hypothesized that reading has more to offer learners than listening, and that the purpose of the classroom should extend beyond a traditional lecture. Peer Instruction is relevant to this study because it provides a solution to the problem on which this project is based; that subject matter expertise for emerging technologies is scarce, and, a mix of productized teaching tools (for knowledge preservation) and flatter social structures (such as peer instruction and mentorship) could facilitate problem solving and new knowledge creation in nascent subject areas.

Table 2 Description of ILO's from course 'Quantum Information', relative to Bloom's Taxonomy. Further, ILO's are qualified according to two constraints, suitability for target group (traditional HE engineering students) and suitability for teaching medium (boardgames)

No	Intended Learning Outcome (ILO)	*Remember*	*Understand*	*Apply*	*Analyze*	*Evaluate*	*Create*	Target Group	Board Game
1	Recognize the notions of quantum superposition and entanglement in the context of quantum information		✓					✓	✓
2	Question the nonlocal nature of reality; perform and interpret an experiment testing nonlocality			✓	✓	✓			
3	Discuss the concept of quantum communication including quantum teleportation and quantum repeaters		✓	✓				✓	✓
4	Compare different protocols for quantum key distribution and random number generation					✓			✓
5	Explain the main concepts of quantum computing, including gates, circuits, and error correction		✓					✓	✓
6	Discuss various quantum algorithms, their implementation, and advantages over classical algorithms		✓	✓		✓			✓
7	Describe different quantum technologies for quantum information processing		✓					✓	✓
8	Analyze, discuss and critique articles on quantum information experiments		✓		✓	✓			
9	Program a simple quantum computer program using one of the available development toolkits			✓			✓		

2 Methods

The Design approach for this project is inspired by the Design Thinking methodology. Passing over *Empathy*, it commenced at the *Define* stage. Here, the intended learning outcomes for a selected course were evaluated with a view to identifying a suitable shortlist that could be addressed using a boardgame as an instructional medium. Thereafter, the game board design was implemented as part of an iterative process of ideating, prototyping and testing. In many instances, both ideating and prototyping occurred simultaneously in the same collaborative design session.

The project culminated in two play test sessions with a small mixed group of postgraduate students, researchers and educators. The first session tested one proposed model for game play whilst the second one tested an alternative proposed model for game play. Each session was concluded in under 60 min, following which, feedback was collected from the play testers via a short questionnaire (Supplementary material).

States and Gates was produced by a cross-disciplinary team across two Universities and three different departments. Working together, the members brought together a skill and knowledge set that extended across instructional design, instructional technologies, quantum technologies and chemical engineering. The benefit of the diversity across the team can be appreciated when one observes that it took just three design sessions to produce the working prototype for which the feedback from the product testing session refers.

2.1 Defining product goals

With a view to specifying an introductory course on Quantum Computing for traditional Engineering students, we consulted a Masters course offered at DTU's Physics department titled 'Quantum Information' (QI). The corresponding intended learning outcomes (ILO's) were evaluated according to two criteria. First, for their suitability for a course where it was assumed that the course recipients may not possess an educational background in Physics and/or Computing, and second, for their suitability to form part of a productized learning tool such as a boardgame.

To qualify the first criteria, each of the ILO's from the QI course were categorized according to Bloom's taxonomy. Studying Table 2, we can observe that ILO's 1, 3, 5 & 7 are most consistent with developing a learner's basic understanding. Given their lower status on Bloom's taxonomy, these ILO's were considered to be more akin to building blocks towards a more sophisticated knowledge of the subject. Hence, they were deemed to be appropriate for a learner group that were new to the subject. Reviewing the ILO's with a view to ascertaining which are suitable for integration into a boardgame, only ILO's 2, 8 and 9 were excluded due to their practical incompatibility. The remaining were added to the shortlist. Combining both analysis, Table 2 also highlights four ILO's that satisfy both conditions. Note that all of the ILO's that were shortlisted as being suitable for our target group were also qualified as being suitable for our teaching medium. Hence, rather than narrowing the search, the second evaluation offers insight into the extent that boardgames could be employed as teaching tools for other aspects of the same or similar courses.

A period of exploration followed, where different combinations of these ILO's were considered in terms of their compatibility in a single product. After some deliberation, it was decided that it would be possible to combine ILO's 1 and 5 into a single board. Here, integrating the notions of quantum superposition and entanglement as part of a quantum computing concept (that includes gates and circuits) within an instruction-based boardgame, appeared to be intuitive. Notwithstanding, other combinations were also deemed feasible, although not explored further in this work.

2.2 Design

The minimum viable product (MVP) for *States and Gates* was designed across three design consultation sessions that were spaced 1 month apart. The game makes use of the Bloch sphere model and two card sets, one representing *states* and another representing *gates*. The team developed several different game mechanics by which to play *States and Gates*. In all versions, the model and cards are used to facilitate unitary operations. However, where they differ is in the outcome of knowing/not knowing the mathematical expressions for a corresponding state or gate. In some versions, knowing the expressions facilitates game progression whilst in others it facilitates the accumulation of points. In this paper, two versions of the game are illustrated whilst other versions are or will be made available on GitHub in due course.

The design elements have been categorized into three groups; Board & Navigation, Game Mechanics and Game Props.

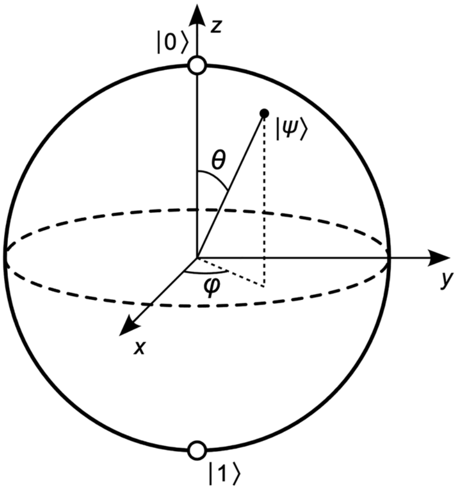

Fig. 1 Bloch sphere CC BY-SA 3.0 [8]

2.2.1 Board & navigation design

The Bloch Sphere was leveraged as a scaffold in the visual design of the board to explicitly promote familiarity with this model of a qubit whilst simultaneously supporting game play/progression.

The Bloch Sphere is presented with 6 pure states that coincide with the z, y and x axis of the sphere (Fig. 1). A double-sided card exists for each pure state. These cards are placed in proximity to their respective location on the Bloch sphere for the duration of the game. For each card, the symbol for the state is visible on the top side of the card whilst the mathematical expression (in the form of their state vectors) is concealed on the bottom side. A deck of cards also exists representing a range of quantum gates. This range includes the I, X, Y, Z, H and S gates, i.e. the identity, the Pauli gates, the Hadamard gate and the phase gate. In common with the set of cards representing the states, the deck of cards representing the gates is also double-sided. Here again, symbols are visible on the top side of the cards whilst the corresponding mathematical expressions (their matrix form) are concealed on the bottom side.

Each player requires a piece to keep track of their current position.

2.2.2 Game mechanics

A critical challenge for the game mechanics was to ensure that the players could continuously progress, regardless of their skill level. Consulting flow theory, we sought to devise a progression path that was flexible enough to support a range of prior knowledge and skills, and aptitudes. Two different approaches to game play were devised for the same board. These were structured as a level 1 and a level 2. Further, two variations were proposed for level 1. Both levels can be played using the same board, albeit in different ways.

2.2.2.1 Level 1 Level 1 is designed as a 2–4 player game where each player competes against all other players on the board. To play level 1, you will need:

- 1 States & Gates Board
- 1 set of 'States' cards
- 1 deck of 'Gates' cards
- 1 piece per player
- 1 scrap-notebook per player
- 1 pen/pencil per player
- 3 'Ask a Peer' tokens (optional)*

2.2.3 Game props

2.2.3.1 The 3D bloch sphere Whilst it is anticipated that matrix multiplication will be the dominant method for assisting players to perform unitary operations, it is also envisioned that students with good abstract reasoning abilities may prefer to employ motor-visual techniques. Therefore, aside from the image of the Bloch sphere on the board, a second (3-dimensional) model will be offered as a tool for this purpose. In a variation of the game not presented here, players have to throw a two-sided coin to establish which method (matrix multiplication or motor-visual rotations) needs to be employed to perform the quantum transformation.

2.2.3.2 The cheat sheet The *States and Gates* cheat sheet is a 2D matrix that provides the solution for each application of a gate to each available state in the game, e.g. the **X** gate acting on state **0** results in the new state **1**. The cheat sheet is designed to be used sparingly, and possibly only by the Game Master, to check that a player has performed the correct transformation. However, it is not impossible to allow individual players to consult this sheet, particularly among teams of newbies.

Illustrations are available in the supplementary material and on our GitHub repository for which a link is provided in the conclusion of this paper.

3 Results

We had an opportunity to test *States and Gates* at a weekend event held at DTU titled *Quantum Computing Applications in Chemical and Biochemical Engineering Workshop* [13]. Seventy participants were in attendance at the weekend workshop, all of whom were, at least, undergraduate students. Of these, twelve elected to join at least one of the *States and Gates* playtest sessions. The sessions sought to validate a few key questions such as '*is the board game appropriate for our intended target group*?' Further, we wanted to gather some insights in relation to the quality of the board game as a learning modality, and its value as an instrument for structuring peer instruction.

To learn more about the suitability of the game for our target market, we asked our play testers to select which of five options about their experience with Quantum Technologies best described them (Feedback survey in Supplementary material). The options ranged from newbie with no previous experience, through novice and intermediary, to expert. 25% of the play testers identified as being completely new to the subject (Newbie), 33.3% identified as possessing some prior exposure via course-based or self-learning, including in combination with research activities (Novice), whilst 25% identified themselves as being involved in research or teaching related to the subject (Knowledgeable). The remaining 16.7% of the play testers left this question blank.

The players were also presented with a set of multiple-choice questions intended to discern from what or whom did they learn during the play test session. The what/ whom options were either teaching tools or people and can be understood as instructional (or teaching) elements. Specifically, the teaching elements consisted of the Board (game), the Game Master and their Peers. The play testers could score these elements as something from which they learned Nothing, Something, or A lot. Nine of the twelve play testers answered this question. Of these, eight responded that they learned at least something from two or more of the instructional elements. Figure 2 illustrates the relationship between the self-assigned knowledge level of the play tester and their perceived value for each of the instructional elements.

1. The two novice groups were combined into 1 group.
2. Researchers and Teachers were added to 1 group and renamed 'Knowledgeable'.

Qualitative responses were converted to numeric values for the purpose of making comparisons. 'Nothing' was assigned a score of 0, 'Something' was assigned a score of 5, and 'A lot' was assigned a score of 10. The results illustrated in the Figure is an aggregate of the results for each group. A more detailed description of the process can be found in the supplementary material.

Examining Fig. 2, one can easily observe that the play testers who identified themselves as being a novice all reported that they learned *A lot* from their peers. Conversely, those players who identified as researchers in a related field either didn't respond or reported that they learned *Nothing* from their peers. Bearing in mind that the sample size is far too small to be statistically significant, however, the authors believe that these initial findings indicate the knowledge/skill level of a group of learners for which this game can effectively form part of a teaching strategy. For *States & Gates*, peer instruction has value when the players are at the early stages of knowledge and skills acquisition, but particularly at the post introductory stage.

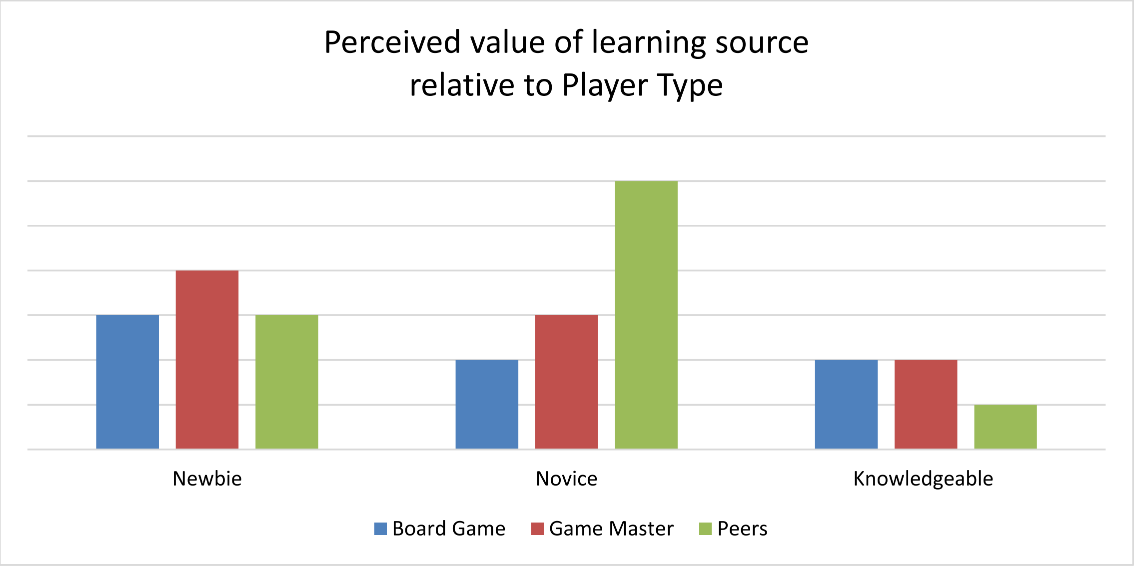

Fig. 2 Value of Instructional device relative to Player competency

Further, and with a view to learning something about the appeal of the games, the play testers were asked several questions. To the question, did they like the game and enjoy the session, the answer was yes in all, but one instance.s. To the questions about aesthetics which specifically related to the size and colours of the board and cards, the answer was positive in all evaluations where a response was provided. And, to a question about whether the instructions were exhaustive enough, the answer was yes in 75% of cases where this question was answered.

Finally, the survey also provided space for comments. Comments for 'What I learned' were as follows:

- *"Quantum Gate switch using Games"*
- *"Basic States & Gates"*
- *"Time evolution of Q-states/gates operations"*

'Other Comments' were as follows:

- *"Excellent"*
- *"We had super fun"*
- *"Fantastic Games! The print out is really nice."*
- *"Great Game for undergrads"*
- *"If you are familiar with Block sphere, the game is too easy"*

Taking together, we believe that the value and the sentiment that was shared by the play testers is an indication that the game has potential and is worthy of further investment.

4 Discussion

In relation to immediate design improvements, several suggestions were provided by the game testers at our testing event. These suggestions were as follows:

1. *"Green cards sorted, not shuffled. Maybe separate stacks for all states/gates for the green ones"*
2. *"Instructions could be more streamlined with examples"*
3. *"I like the idea of the 3D model but found it difficult to identify states on the cardboard version"*
4. *"It could be clearer that the piece has to jump according to the operation. The game seems to be very simple, once you see the pattern"*

5. *"(develop) Easier way to error check without cheat sheet"*
6. *"Having the cheat sheet makes it a searching issue so you should penalize using it."*
7. *"I think the response should be checked somehow, maybe by other teams"*

To date, suggestions 1–4 have received some consideration. Here, improvements to the board, cards and instructional design have been implemented. Meanwhile, suggestions 5–7, which we believe require a digital solution, have been added to a list for future work.

In its current form, *States & Gates* is a minimum viable product in analogue form. Further, whilst analyzing the ILO's for the Quantum information course, it was identified that several other learning objectives could be addressed using board games. As such, there are several opportunities to improve or expand on this current work. These include pedagogical and design options such as:

- Improving the Cheat Sheet functionality using a digital interface.
- Utilizing digital technology, mixed reality in particular, to combine the 2D and the 3D Bloch sphere into a single asset.
- Expanding the current offering to more games.

Further, and for a more rigorous approach to user testing; the nine channel model of subjective experience [14] which is inspired by flow and intrinsic motivation [10] and useful for plotting and identifying flow channels, could be consulted to further explore the immersive value of the games.

5 Conclusion

This paper presents an instructional design tool to introduce (Chemical) Engineering students to the subject of Quantum Computing. The project is motivated by a concern that, if technologies continue to evolve at an accelerated rate and if the number of subject matter experts diminishes in turn, productized learning tools will be required to play a larger role in knowledge transmission and development. At the same time, learning is social, and compatible learning theories such as Social Constructivism [15] and Peer Instruction [11, 12] can be facilitated using the modality of boardgames.

In this project, we developed a board game called *States & Gates* to introduce higher education engineering students to the subject of quantum circuits. The findings from our initial play test session suggest that peer instruction is a pedagogic aspect of playing the game, and that this form of instruction, as perceived by those engaged in testing this learning process, is most effective at the novice stage of learning, Fig. 2.

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QuantumStatesAndGates.

Author contributions D.E.C.: Conceptualization, Methodology, Product Design Lead, Product testing, Writing- Original draft preparation. J.N.N.: Conceptualization, Product Design, Scientific discussions, Writing- Reviewing and Editing. E.v.N.: Product Design, Scientific discussions, Writing- Reviewing and Editing. M.P.A.: Product Design, Scientific discussions, Product Testing, Supervision, Writing- Reviewing and Editing.

Data availability All data used are available as part of the publication and the supplementary material.

Declarations

Competing interests The authors declare no competing interests.

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