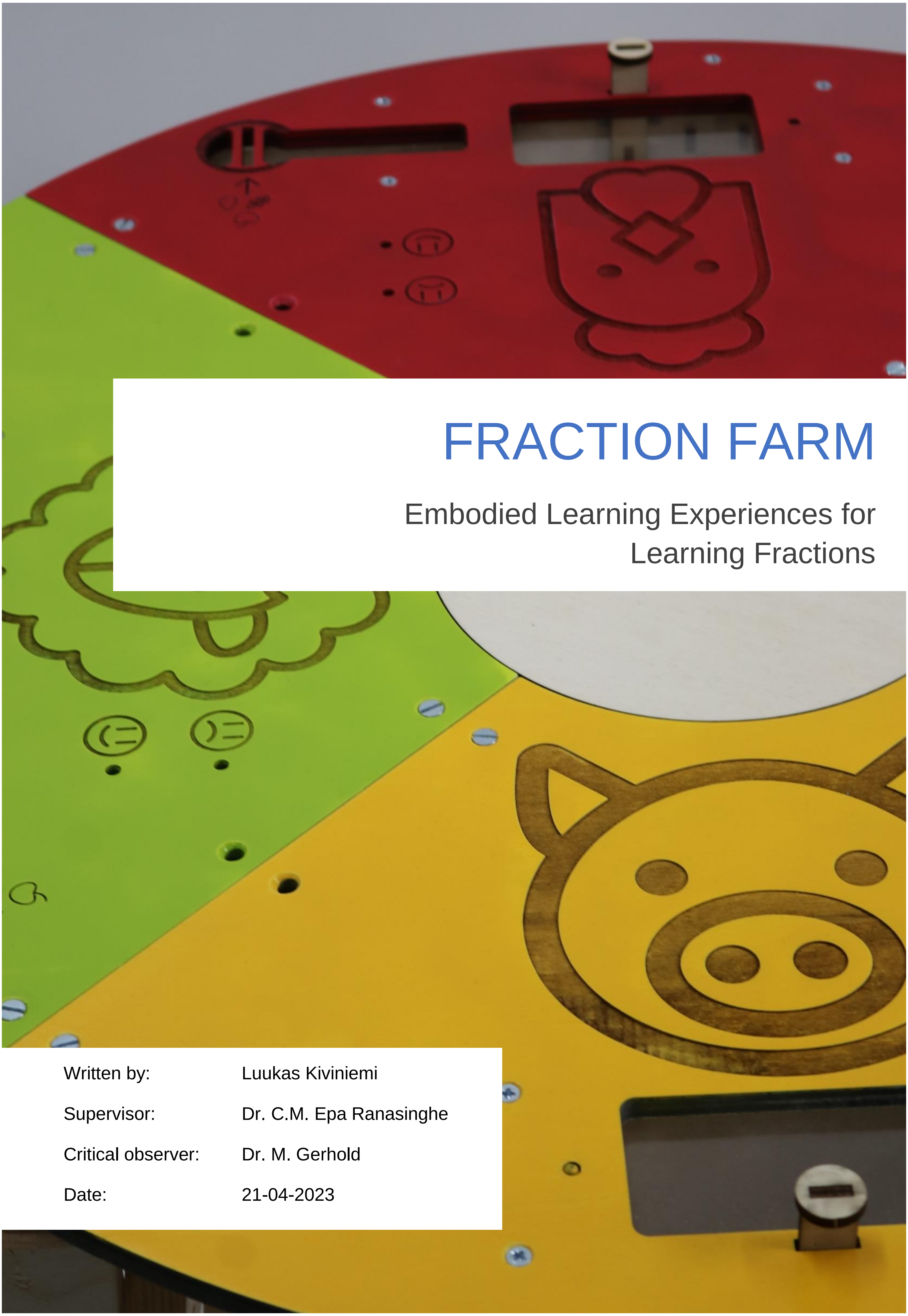

FRACTION FARM

Embodied Learning Experiences for Learning Fractions

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Date:	21-04-2023

ABSTRACT

Tangible learning tools are pedagogical tools that utilize the intuitiveness and physical nature of tangible interfaces for learning purposes. When designed correctly, these systems can provide improvements to learning gain, knowledge retention and understanding of abstract concepts, whilst simultaneously being fun and engaging to use. As the quality of education in the Netherlands has been stagnating for the last couple decades, and the COVID-19 pandemic led to many setbacks in education, new methods for teaching could provide solid improvements to the struggling system. Together with the benefits of tangible learning tools, this provides ample motivation for the development of these tools for classroom use. For this research, introductory fractions were considered specifically. The subject of fractions is often difficult for young children in primary schools to grasp, as it presents a completely new meaning for numbers and what they relate to. A tangible learning tool could be a great way to help children get familiar and comfortable with fraction concepts. As such, a tangible system for learning fraction concepts named Fraction Farm was developed. Through design frameworks for tangible learning tools, the system was designed with a focus on creating a fun, engaging and collaborative experience, while allowing children to engage with fractions in a tangible and context based manner. A prototype of the system was built and qualitatively evaluated in a real world context. The results of the study indicate that Fraction Farm is fun and engaging to use and enables both collaboration and tangible interaction with fractions. This research does not yet proof that Fraction Farm has any impact on the learning of fraction concepts, but the results of the study do indicate that the system could have potential and should be developed and researched further.

ACKNOWLEDGEMENTS

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CHAPTER 1. INTRODUCTION

Education in the Netherlands has been struggling in recent years. Reports from the Dutch government have shown that the quality of education in the Netherlands is decreasing compared to 20 years ago [18]. This has further been compounded by the recent corona crisis, leading to a lot of learning objective backlogs in primary schools [19]. Especially when it comes to math there has been a significant reduction in learning growth [19]. Looking at these problems it is evident that education in the Netherlands is due for change.

Based on the current methods used to teach children, it is important that these methods match the needs and cognitive function of the children. In the last couple decades, views within cognitive sciences supporting the theory of “embodied cognition” [5] have become more mainstream. The theory argues for the importance of the body and embodiment within cognition (and by extension learning). Subsequently, these views have been taken up by designers. This has led to numerous studies which incorporated the theory into learning tools and tested them in classrooms, many providing positive results.

Tangible learning tools allow users to interact with learning material in a more embodied manner. Compared to less embodied ways of teaching, these tools have been shown to have positive effects on learning gain [3], knowledge retention [4], as well as the capacity to grasp abstract concepts quicker [12] (provided that the tools are well designed and implemented). Additionally there are indicators that physical engagement with manipulatives can be very beneficial to the reinterpretation of prior knowledge [8]. Considering the cognitive benefits of tangible systems in learning, it is warranted to explore their potential in classrooms further.

This project concerns the development and evaluation of a tangible learning tool aimed at helping teaching basic fraction concepts in an engaging way to primary school children. Fractions were chosen as the focus, as they are a tough concept for many students encountering them for the first time. They are exemplary of difficult abstract concepts, requiring reflection, dissolution and reconstruction of knowledge, allowing for a tangible learning tool to act as a catalyst in that process [8]. The intended use of the learning tool would be as an addition to existing traditional teaching methods that teachers already use, not as a replacement of the teacher or existing methods.

Broadly, the project aims to add to the body of knowledge regarding tangible learning and help create educational tools which make our education more effective and attuned to students’ needs and cognition. More specifically, the project aims to explore:

- *How embodied and tangible learning concepts can be incorporated into a learning tool for assisting the teaching of basic fraction concepts to Dutch primary school children (aged 9-10) in an engaging, enjoyable and collaborative way?*

By developing a learning tool that:

1. Effectively applies embodied and tangible learning concepts for learning fractions
2. Makes the learning process of fraction concepts more enjoyable and engaging
3. Facilitates collaboration in the learning process of fraction concepts

To fulfil these goals, a prototype was designed and constructed. Various theories, guidelines and research related to tangible learning were used within the development process, with the Tangible Learning Design Framework by Antle and Wise [9] serving as the central framework.

The prototype was subsequently evaluated through a small scale user study at a Dutch after school care with 8 children. Results from the user study show that the prototype was engaging and fun to use, triggered a lot of interaction between participants and enabled embodied interactions to some degree. To gain concrete information about Fraction Farm's impact on learning fraction concepts and its role in a classroom, further research and development would still be necessary however.

CHAPTER 2. RELATED WORK

Paper based learning methods have been the norm in education for a long time. These methods tend to be designed based on a view of cognition that places our capacity to learn and express abstract concepts solely in the brain, with the rest of the body being of little significance. In the last couple decades however, there has been a rise in the research and development of so called tangible learning experiences (TLE's). These systems focus on creating intuitive and physically tangible interactions with the learning material, allowing students to interact with concepts and learn in a more natural way. The theoretical backing for these systems argues that learning is in fact strongly tied to physical interaction, instead of being an isolated process in the brain [5] [10]. It also argues for the benefits of mapping specific actions and elements of a learning interface to general and familiar real-world entities [9], [14], [3], [9], [11].

This chapter briefly describes the underlying theories related to tangible learning, frameworks for designing TLE's and finally examples of developed and researched TLE systems. Based on the theory and findings of related studies we finally describe the potential benefits of TLE systems.

2.1 THEORETICAL FRAMEWORK RELATED TO TANGIBLE LEARNING

The theory underlying tangible learning stems from cognitive sciences and human computer interaction (HCI). In the following part both the cognitive science aspects (*embodied learning*) as well as the HCI aspects (*tangible user interfaces*) are discussed, together with frameworks for designing TLE's.

2.1.1 EMBODIED COGNITION

In [5], the theory of embodied cognition is stated to be premeditated on the idea that cognition does not merely exist in isolation within the nervous system. Instead, they argue that cognition is dependent on our bodies' sensorimotor capacities, with our bodies acting as both constraint and enabler to cognition. [5] further points out that, as our cognition is contained within our bodies, our capacity to relate to and learn from the world is necessarily tied to how we interact with the world using our bodies. Additionally, [10] lists certain views within the theory that even see the body as the starting point of cognition, arguing that we evolved from creatures that used cognition solely for immediate reactions to their environment.

Embodied cognition becomes most relevant to education when considering how it argues that memories and mental concepts are shaped through physical interactions with the world. Both [5] and [10] point out that there is substantial evidence that points to many cognitive processes previously seen as abstract and isolated, to be rooted in embodiment; Memory, reasoning and problem solving all seem to make use of sensorimotor simulation.

Finally, [10] lists another important facet of embodied cognition that is relevant to learning: the use of environment to *off-load* cognitive tasks and information. Here the environment serves as a storage for information and as support for cognitive tasks. By manipulating our physical surroundings (or ourselves in relation to our surroundings) we store information physically so we do not have to do so mentally. Examples of this are using your fingers to count or writing something down.

2.1.2 TANGIBLE USER INTERFACES

Another central concept regarding TLE's is the theory surrounding tangible user interfaces (TUI's). Broadly speaking, TUI's are interface systems designed around physical and intuitive interaction. According to [3] and [9], they strongly focus on integrating familiar ways of physically interacting with everyday objects into the interface design. While some papers give more narrow and specific definitions for a TUI, the variety amongst systems which have been presented as TUI's is great [11]. For the context of this report, TLE's are broadly described as systems which apply TUI's in a learning context.

[11] gives a very broad definition which can be cast to apply to most of these systems. Their definition says that a TUI is a system which *senses* and *processes* an *input event* (usually the manipulation of some physical object) to produce an *output event* (some alteration to the physical nature of an object). As this definition is so general, [11] proposes a 2 dimensional taxonomy to distinguish between different levels of tangibility. The dimensions for this taxonomy are *embodiment* and *metaphor.* Embodiment describes the degree to which the input is tied to the output. The more embodied an interface is, the more the input and output device become one and the same. Metaphor describes how the reactions of the system map on to real-world reactions to similar actions. The more metaphor an interface has, the more the system becomes one and the same with its analogous real-world counterpart.

[11] states that all TUI's exist somewhere in this 2 dimensional spectrum, where systems with high embodiment and metaphor have more tangibility, and systems with low embodiment and metaphor have less tangibility.

2.1.3 TANGIBLE LEARNING

Based on the aforementioned theories as well as other theories related to cognition and learning, numerous frameworks for designing TLE's have been constructed. [9], [8], [14] and [2] are all examples of proposed frameworks for approaching TLE design.

The framework of Physically Distributed Learning [8] describes four ways in which physical actions can support thinking and learning (see figure 1), and how physical actions on manipulations can be beneficial to learning fraction concepts.

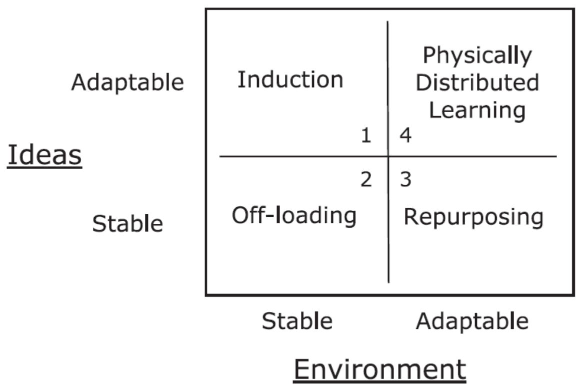


Figure 1. The four ways in which physical actions can support thinking and learning [8].

Induction describes systems where more mature understanding of the environment is constructed by manipulating a stable environment. *Off-loading* describes systems where users learn to more effectively manipulate a stable environment for storing information and simplifying tasks. *Repurposing* describes systems where users learn new ways of manipulating their environment to adapt to an adaptable environment. Finally *Physically Distributed Learning (PDL)*, which describes systems in which learning takes place through functional adaptations both in the individual as well as in their environment. Most TLE systems fall within PDL. PDL is particularly relevant to TLE's and the learning of fractions specifically, as a TLE system for teaching fractions needs to help adapt the user's understanding of numbers through the adaptable interface of the TLE.

The Tangible Learning Design Framework by Antle et. al. [9] is an example of a more pragmatic framework, providing a robust set of design guidelines for the design of TLE's. It describes the design space of TLE's through guidelines on the design of: the *actions* by the learners afforded by the system, the *physical* and *digital objects* that the system consists of, the *informational relations* mapping the different objects and actions to real world entities, and *learning activities* describing the framing of the system through context, guidelines and instructions for using the system (see figure 2 for a graphical representation).

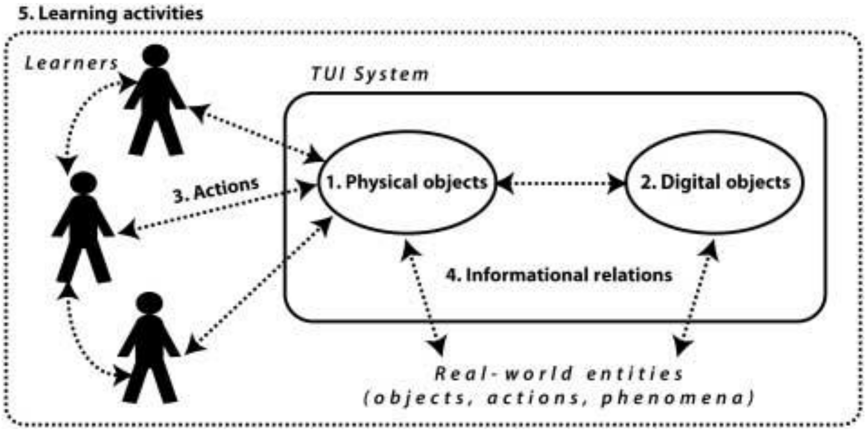


Figure 2. The 5 elements of TLE design described in the Tangible Learning Design Framework [9].

Proper TLE design would require proper design of each of these elements, considering the underlying theories for each element. The framework establishes 12 design guidelines related to these elements, through different domains related to TLE design.

Within the framework, [9] roughly defines 5 domains as follows. The first domain, *information processing*, largely pertains to cognitive processes related to working memory and cognitive load. A distinction is made between *germane* cognitive load, which benefits learning, and *extraneous* cognitive load, which is cognitive load created by distracting elements. The second domain, *constructivism*, considers the importance of interacting with the world for constructing knowledge. The third domain, *embodied cognition*, pertains to the importance of the body and physical interaction in cognition (as described in the previous part). The fourth domain, *distributed cognition*, describes the importance of physically manipulating the environment for cognitive processes and learning. The final domain, *collaborative learning*, regards the importance of social and collaborative activities within learning.

Earlier work by Antle in the CTI (Child Tangible Interaction) Framework [14] proposes a framework with a similar focus. It puts strong emphasis on the design of the physical and behavioural mappings and affordances of TLE systems, as well as the importance of designing for collaboration.

2.2 APPLYING TANGIBLE LEARNING IN THE CLASSROOM

There is a wide variety of TLE systems which have already been developed and tested in classroom contexts. These systems utilize a wide range of technologies in their interfaces, as well as varying degrees of embodied interaction design. The following part focuses on developed systems and their described learning benefits, considering papers that pertain to relevant systems and the results of their user studies.

2.2.1 EMBODIMENT AND MEMORY RETENTION

Starting off with [6], in which the benefits of a TLE named IMAGINE (Immersive Multimodal Ambient Gymnasium IN Education) are evaluated. The system was developed to serve as a more effective pedagogical tool compared to traditional paper based classroom methods. The main components of the system consisted of projections on the floor and wall and a Kinect v2 motion sensor. Students could interact with the system by touching the digital projections on the ground and floor, while a teacher could control the lesson through a tablet.

In [6]'s user study, IMAGINE was tested amongst primary school children aged 6-8 and evaluated on students' memory retention after using the system. Test results were compared to a control group learning the same concepts through traditional paper based methods.

The results from their user study showed that the students using IMAGINE had significantly better knowledge retention compared to the control group. In their discussion, [6] states that their results could be attributed to the immersive and embodied experience offered by IMAGINE, arguing that it *"eventually enabled children to encode information more naturally, to consolidate it through embodied reflection, store and recall more easily and for a longer period."*.

2.2.2 INTERACTION MODALITY

Considering [11]'s earlier definition for TUI's in section 2.1.2, it follows that embodied learning experiences can be created using a wide variety of interaction modalities. These modalities can be more or less tangible, or not at all.

In [4], 4 different interface systems for teaching human anatomy were evaluated relative to each other. Each of the interfaces utilized a different interaction modality, either tablet, tangible, motion-based or multimodal. The multimodal interface contained both tangible and augmented reality elements.

Similar to [6], [4] evaluated students' knowledge retention after using the learning systems. In their user study, students' post-test performances were compared relative to the performances of students that had used different systems. From their results it showed that students that had used the more tangible interfaces (tangible, motion-based and multimodal) had significantly higher long term knowledge retention compared to the group that used the tablet. Additionally, when comparing the more tangible interfaces, students that had used the multimodal interface performed the best out of all the interface modalities.

Both these findings further point to the significance of embodiment and tangibility in learning. According to [4], being able to map gestures and physical manipulations onto concepts seemed to have allowed the children to create more concrete associations. Allowing them to do so through more than just one modality seemed to have further improved this effect, as it enabled them to interact in a way that was most natural to them. The latter point is also supported by [1], where it is argued that students' capacity to express and form understanding of a concept is facilitated and limited by the available media that they can utilize to encode said concept into.

2.2.3 CONCEPT AND METAPHOR

Finally, we consider an example of a TLE system which relies on the role of metaphors in TLE's. Moving Sound (MoSo) Tangibles is an interactive learning environment developed by Bakker et. al. [12]. It aimed to teach abstract sound concepts to children. The learning tool consisted of 3 sets of interactive artifacts, each focussing on teaching one of the following concepts: pitch, volume and tempo. By moving each of the artifacts, students could manipulate piano tones, with each artifact affecting their respective concept.

The system was designed such that students had to interact with the artifact in a manner that served as a metaphor to the respective sound concept. For example moving an artifact from a low to a high position would shift the pitch from low to high.

From their user study, [12] found that all of the participants were able to reproduce sounds and tempo's using the artifacts, despite not all of them being capable of explaining the underlying concepts verbally.

[12] argued that this showed how embodied interaction could serve as a scaffold for understanding and expressing abstract concepts. The metaphoric link between the action and the concept would have allowed the children to gain a more intuitive understanding of the concept and provided a stepping stone to conceptual understanding.

The importance of this kind of intuitive interaction is also supported by [1]. They argue that students construct new meaning from instrumentalizing semiotic tools to describe abstract concepts.

2.3 CONCLUSION: THE POTENTIAL BENEFITS OF TLE'S

Considering both the theoretical background and empirical findings regarding the effectiveness of TLE's, we can describe some of the potential benefits of TLE systems.

First and foremost, TLE's allow students to interact with concepts in a more embodied manner. As the empiric studies in both [4] and [6] show, students that learned using methods that allowed for embodied interaction tended to remember the lesson materials better. The benefit of embodied interaction with concepts is further supported by the theory of embodied cognition presented in [5] and [10], which argues for the critical role of physical interaction in cognitive development. Accordingly, it would seem that a learning method which considers the importance of embodiment will be more effective than one that marginalises it.

Additionally, TLE's allow for a wide range of interaction modalities. Considering [4] and the results from their user study, interfaces that allow for multimodal interaction seem to be the most effective when it comes to knowledge retention. This also makes sense when taking into account the aforementioned importance of embodiment, as a wider range of possible interactions would allow for more embodied interaction.

Finally, by using metaphors, TLE's connect abstract concepts to concrete objects and actions. Looking at [12], it is evident how metaphoric actions enabled students to express understanding of abstract sound concepts physically, even though they were unable to express said concepts verbally. This seems to point to metaphors helping students with grasping abstract concepts.

It is important to note however, that the empiric studies in this review only contained children between 8 and 12 years old. Children of different ages might respond differently, making TLE's less effective. Furthermore, the studies did not consider the social aspects of learning, which various sources within the field of TLE's ([9], [14]) consider to be significant.

CHAPTER 3. METHODS AND TECHNIQUES

Taking inspiration from the established work surrounding TLE's, a tangible learning tool for learning fractions called Fraction Farm was developed and evaluated. The following chapter briefly outlines the design process and evaluation of the prototype.

3.1 DESIGN PROCESS

The development of the prototype was done in 3 phases: ideation, specification and finally implementation.

At the start of the ideation phase, a set of central design considerations related to tangible learning design as well as the intended use of the system were established. These design considerations are described in chapter 4. Based on these considerations some rough initial concepts for the learning tool were created and considered.

After ideation, one concept was taken and refined further during the specification phase. Further design considerations for that specific concept were established, together with a list of necessary features and the technologies necessary for implementing these features and considerations. At the end of the specification phase a final concept was put together, describing all the elements of its design and how the system would be used.

Once the final concept was established, the design could finally be implemented into a fully functional prototype. During the implementation phase, design and construction of all the necessary parts of the prototype took place, together with the programming of the various electronic parts.

The previously mentioned Tangible Learning Design Framework by Antle et. al. served as a backbone to the design choices made throughout the design process. By regularly referring to the framework, the design remained grounded in the underlying theory. The framework describes 12 design guidelines across 5 domains within the field of tangible learning. Each of these guidelines is linked to the elements (see figure 2) of TLE design that are relevant for implementation of said guideline. This provides a very clear overview of the central theories and in which elements of the system they are relevant. See table 1 for the guidelines.

3.2 EVALUATION

In order to evaluate the design choices and test how the prototype would hold up in a real world context, a user study was conducted. The study was aimed at evaluating the enjoyable and engaging using the prototype was, as well as to what degree using the prototype led to collaborative and embodied engagement with fraction concepts.

Participants were recruited through an existing partnership between the University of Twente and after school care BSO De Vlinder. An outline of the study design was submitted to the University of Twente EEMCS ethics board and subsequently approved. After obtaining ethical approval, the user study was conducted on location at the after school care located at the University of Twente campus. During the study, the participants (children aged 6-8) interacted with the prototype and answered question relating to their experience of using the system. Data was collected through these questions, as well as observations.

The works by Read et. al. [13] and Hanna et. al. [15] describing methods and guidelines for usability testing with children were central to the study design and the data collection methods and techniques. Chapter 5 goes more into detail of the exact methods used for the user study.

Perspective	Guidelines	Physical objects	Digital objects	Actions on objects	Informational relations	Learning activities
Info processing	1. Distributing information across modalities can increase effective working memory capacity	X	X			
	2. Making mappings between the form and behavior of physical and/or digital objects and real-world entities coherent can reduce extraneous cognitive load				X	
Constructivist	3. Creating authentic tasks and using personal objects can support learners in forming individually meaningful goals for interacting with the TUI	X				X
	4. Using spatial, physical, temporal or relational properties can slow down interaction and trigger reflection	X	X	X	X	X
Embodied	5. Distributing parts of mental operations to actions on physical and/or digital objects can simplify and support mental skills			X	X	
	6. Leveraging image schemas in input actions can improve usability and system learnability			X		
	7. Using conceptual metaphor(s) based on image schemas to structure interaction mappings may bootstrap learning of abstract concepts				X	
Distributed	8. Designing objects that allow spatial reconfiguration can enable mutual adaptation of ideas	X	X			
	9. Using concrete representations can support interpretation of symbolic representations of abstract concepts	X	X		X	
Collaborative	10. Creating configurations in which participants can monitor each other's activity and gaze can support the development of shared understandings	X	X			
	11. Distributing roles, information and controls across the TUI learning environment can promote negotiation and collaboration	X				X
	12. Creating constrained or codependent access points schemes can compel learners to negotiate with each			X		

Table 1. The Tangible Learning Design Framework by Antle. et. al.

CHAPTER 4. DESIGN & IMPLEMENTATION

4.1 IDEATION

For the ideation of the to-be-designed learning tool, the most important design constraints and requirements had to come from the material it is supposed to teach as well as the purpose and intended use of the prototype.

4.1.1 DESIGN CONSIDERATIONS

Considering fractions, the material to be taught, there are important considerations for potential designs.

REAL WORLD CONTEXT

Firstly, it is important to leverage the real world context in which children are already introduced to fraction concepts. The most common real world application of fractions is resource management. Children from an early age can already conceptualize how to fairly divide a group of objects or one large object fairly between multiple parties, without having any formal knowledge of division [16]. For example if a group of 4 children would have 4 candies, or a cake, that they have to divide amongst themselves. As these kinds of activities most commonly take place with peers, peer interaction and collaboration seem to be a natural part of these kinds of activities. A learning tool that helps to introduce fractions to children for the first time should therefor leverage these kinds of division activities and their social nature to build new knowledge on a foundation of what they already know.

BRIDGING CONCRETE AND ABSTRACT

Secondly, a natural bridge between concrete and abstract representation needs to be created. The abstract representation of the fraction 1/3 can be represented concretely and physically by taking an object, cutting it into 3 equal parts, and finally removing one of the pieces. In order for a child to grasp the abstract meaning of a fraction, they need to be helped to connect concrete representations to the abstract numerical representations of fractions. [8] further points out that fractions are also complicated because they require the reinterpretation of prior knowledge. Before being introduced to fractions, numbers merely represent discreet amounts and points on a number line, whereas with fractions they now describe the relationship of a part to a whole. Interacting with a concrete representation can help with this reinterpretation process (when implemented correctly [16]).

PHYSICAL INTERACTIONS

Third is the role of physical interaction. In order for the prototype to enable effective tangible interaction, physical interactions need to be implemented in a way that makes sense for teaching fractions. According to [8], it seems that the use of manipulatives (small movable objects) is an intuitive and effective way for children to interact with fractions. Looking at the previous 2 considerations, manipulatives also make sense, as they can easily be linked to a real world context as well as an abstract representation simultaneously.

INTENDED USE

Regarding the intended use and purpose of the learning tool, the goal was to not try to replace the teacher. The learning tool should serve as an addition to the teacher's tools, assisting them in teaching this difficult concept. [16] points out that working with concrete representations alone can potentially be adverse for gaining understanding of abstract concepts (particularly when not implemented properly). Accordingly, while the learning tool should make the connection to underlying abstract fraction concepts clear, engagement with fractions in a more purely abstract and non-concrete manner is still very necessary. As such, the learning tool should just operate as a tool for teachers to help bridge the initial knowledge gap through tangible interaction and concrete representations.

Tangibility also has an important role to play regarding the intended use of the learning tool. A big advantage of tangible interfaces for learning is that they tend to make the learning process much more engaging for the children. This is can be a valuable asset for a teacher, as it can help their students create a more positive association to learning fractions (it being a difficult and therefor also frustrating and potentially demotivating subject to learn).

Furthermore, interaction needs to be suitable for a range of proficiencies with the subject. Both students with a capacity to quickly grasp fraction concepts and those who have a hard time understanding it should be able to use the system. Ideally, the system enables and encourages the students who understand the concepts to assist the students who are having a harder time doing so.

Finally the learning tool should allow for multiple children to use it simultaneously and engage them in interacting with the learning material in a collaborative fashion.

4.1.2 INITIAL CONCEPT

Based on these considerations a rough initial concept was constructed. With this design, children would learn fraction concepts by moving manipulatives onto various zones. Children would have to either distribute a group of objects based on a given fraction, divide an object based on a given fraction, or unite parts of a whole. Every assignment would be framed in a real world context to ground the tasks on the children's existing knowledge. To further flesh out this concept, a description of how it would be used with an example assignment for this initial concept was created.

INITIAL CONCEPT LESSON DESCRIPTION

The goal of this lesson is to teach the concept of one half. The concept will be introduced in 3 ways:

1. dividing an object into 2 equal parts;
2. combining 2 parts to create a whole;
3. dividing a set of objects into 2 groups of equal number.

All of the exercises can be performed collaboratively or individually. The exercises take place on top of a table, where they have to distribute physical objects into the correct areas. The areas that the objects need to end up in have fractions written on them corresponding to the fraction of the object(s) that need to be moved there.

Each of the exercises will be preceded with an audible explanation regarding the assignment and the scenario in which it takes place. For the 1st exercise it is *“There is one pastry left. Both you and your friend want a piece. Divide the pastry in such a way that both of you have the same amount.”*.

In the 1st exercise the student(s) will be faced with a table that is divided in 3 areas; a central area containing a divisible object and 2 areas where the halves should be moved.

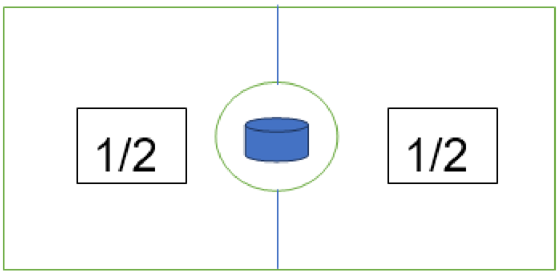


Figure 3. 1st exercise of the initial concept

In the 2nd exercise the student(s) will be faced with a similarly divided table. This time the 2 outer areas contain one half and they have to bring them together in the centre to create a whole. The description for this assignment is: *“A bowl has fallen on the ground and shattered into two pieces. Stick the pieces together again to make it whole.”*

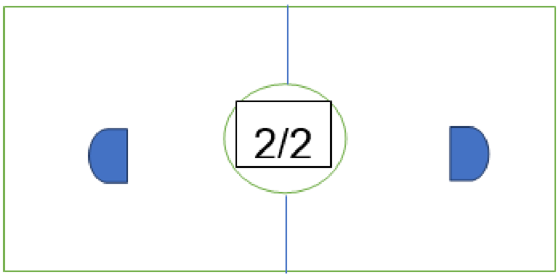


Figure 4. 2nd exercise of the initial concept

In the 3rd exercise the student(s) will once again be faced with the divided table. Now the central area contains a group of 6 objects which have to be divided evenly over the two other areas.

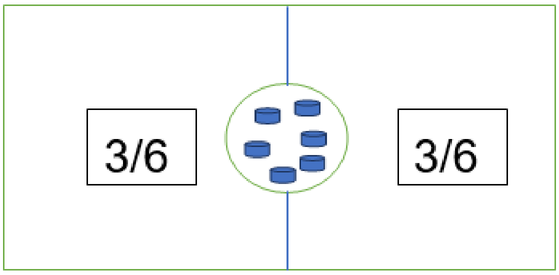


Figure 5. 3rd exercise of the initial concept

The description for this assignment is: *“You and your friend got 6 euro’s to go buy sweets. You both want different things so you decide to divide the money between yourselves. Divide the money in such a way that both of you have the same amount.”*

4.1.3 SECOND CONCEPT: AUTHENTIC TASKS

For the second concept, the initial concept was adapted to be more in line the Tangible Learning Design Framework [9]. This concept also had a higher focus on creating an engaging an rewarding user experience. Some gamification concepts were adapted to this end.

Looking at the design guidelines, the initial concept seemed to be lacking specifically with regards to guideline 3.

> *"Guideline 3: creating authentic tasks and using personal objects can support learners in forming individually meaningful goals for interacting with the TUI (design of physical objects and learning activities)."*

In order to create authentic tasks, the new concept was developed with a more gamified context, while still staying in touch with how children are already familiar with division in a real world context. Instead of more mundane everyday situations as described in the initial concept, the new concept framed the learning activities as the user distributing food to various common farm animals. Assignments would consist of correctly dividing a set of 3 different food / consumable objects across 4 animals. The learning tool would consist of a round table with 4 zones, each assigned to a different farm animal, and these 3 sets of food objects.

Considering the food objects, these would still represent the different ways in which fractions can be represented concretely (a piece of one object or set of objects belonging to a group). This could be done by utilizing icons and / or the shape of the objects. Objects of one type could look like fragments of a whole, becoming a clear whole shape when put together. A different set of objects could be unified in shape, clearly showing that they belong to a group.

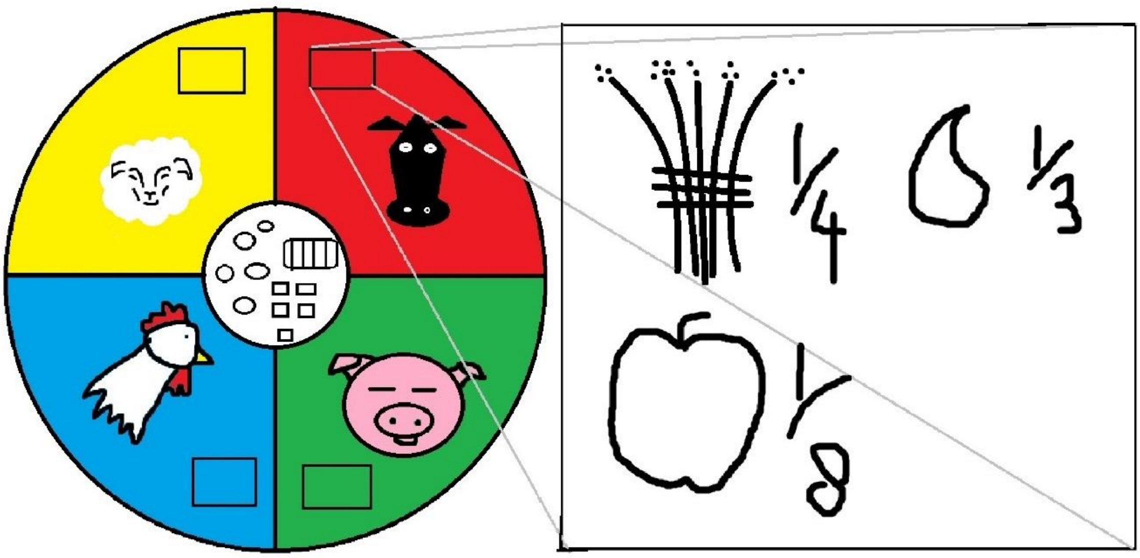


Figure 6. First sketch of the second concept. The round table contains icons for each of the animals (sheep, cow, chicken, pig), together with small areas where the assignments are described. The centre contains an area to store all the food objects (grain, water and fruits) at the start of an assignment.

The goal of this concept was to leverage children's creativity and playfulness. By creating this animal feeding narrative, together with the use of bright colours and simple icons, this concept was made to be playful and fun looking. It could enable the children to identify more with the tool and provide a higher chance to create an intrinsic motivation [17] for using the system. It aimed to make the children want to solve the assignments correctly not just because they would have to complete a task, but also because they were immersed into the narrative and because the system would be fun to look at and interact with.

To further build authenticity and intrinsic motivation, the assignments that children would complete would start off easy and then build up in difficulty. This way it would enable the children to get familiar with using the tool and the fraction concepts, while providing adequate challenge and a sense of progress.

Furthermore, the circular design with different distinct zones also promotes using the system with multiple users and enables multiple users to collaborate and monitor each other's actions. This would take into account the guidelines regarding collaboration from [9].

Finally, the manipulatives within this concept could be moved and touched freely. The only predefined actions that children would have to perform with them would be:

- Collecting all the objects in the centre at the start of an assignment;
- Moving the correct amount of each object to the correct animal zone to complete an assignment.

While trying to come to the right answer, the children would be free to manipulate the objects in any way that they would see fit. This way the learning tool would allow the children to arrange the objects in the ways that are most helpful to them, enabling cognitive offloading [10] [9] and exploration.

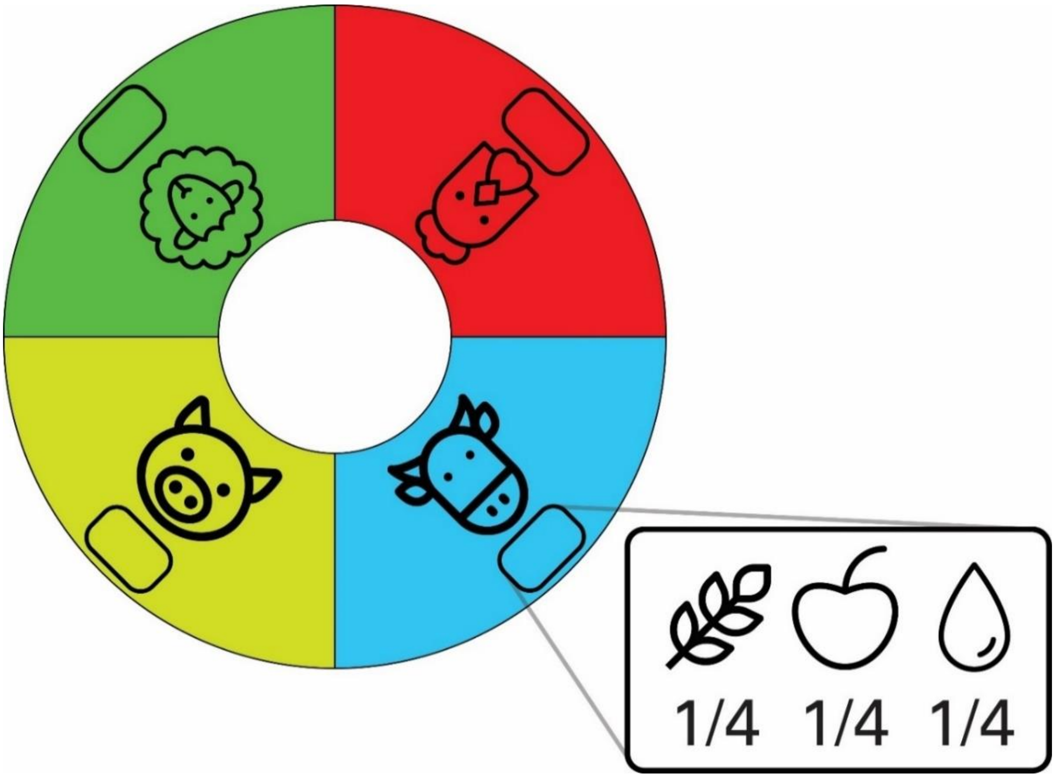


Figure 7. More refined sketch of the farm concept, utilizing simple yet clear icons for the animals and food / water objects.

4.1.4 FEATURE EXPLORATION

REWARD MECHANISMS

Additional reward mechanisms were also considered for the second concept. Completing an assignment could reward the participants with a token of some sorts. These tokens could depict the animals that they fed or the food that they fed them. When more difficult assignments would be completed, this could then be rewarded with a different token to further stimulate and reward learning progress.

ANIMATIONS

In order to make usage of the learning tool more clear and enable children to use the tool more autonomously, introductory animations could be utilized. The setting and the rules of the learning tool could be introduced through a short animation with a voice over.

Animations could also be used for additional instructional videos in case children struggle with certain assignments. This could alleviate frustrations and potentially speed up the learning process.

Finally, the animal face icons could also be animated to further strengthen the farm animal narrative. When animals are fed the correctly they could look happy, whereas an incorrect answer could make the animal look sad. This could further increase intrinsic motivation by making the children identify more with the animals and not wanting to make them sad.

4.2 SPECIFICATION

Building on the initial conceptualizations, the design was narrowed down further. Taking the second concept as a starting off point, the design considerations were reconsidered together with more specific considerations relating to the farm concept. Based on this, a list of features and interactions was constructed, together with the technologies that could be used to implement them. From these considerations, features and technologies a refined final version of the design was created

4.2.1 SPECIFIED DESIGN CONSIDERATIONS

Looking at the design considerations from the start of this chapter, the second concept addresses all of them quite well.

- Leveraging real world context is done through the animal feeding narrative,
- Abstract fraction concepts are linked to concrete representations of food that need to be distributed,
- Physical interaction is implemented through the food object manipulatives.

The concept also brings with it some specific considerations. Which animals should be represented and how many? Which foods or consumables and how many? How difficult should the assignments be? How many users should use the system at a time? How do users get feedback and how does the system facilitate users to learn from their mistakes? Finally, how complex should the overall learning tool be (how many features and different components and interactions)?

ANIMALS

Regarding the animals, the choice was made to stick with the original 4 animals (cow, sheep, pig and chicken). These are all very common farm animals often associated with farms and feeding animals. They are easy to recognise and simple to represent graphically. The foods that these animals eat are also generally well known even to children.

NUMBER OF USERS

The choice to stick to 4 animals also relates to the number of users that could use the learning tool simultaneously. As mentioned earlier, the second concept was already designed with collaboration in mind. A table with 4 animal zones makes the most sense to be used by up to 4 users simultaneously. More than 4 simultaneous users would complicate collaboration and make it hard to keep an overview of the assignment and what everyone is doing. 4 animals also still make it possible to do assignments by yourself, without the assignments becoming too complicated.

CONSUMABLE OBJECTS

The consumables that the objects would represent were chosen to be grains (represented by a bundle of grains), water (represented by a water droplet) and fruits (represented by an apple). These consumables were chosen as they are all things that are familiar to children, as well as being things that are relatively normal (at least not harmful) to feed to the chosen farm animals. These objects are also simple to represent through icons.

ASSIGNMENTS

The number of food object types and animals also affect the complexity of the assignments. As this learning tool is meant as an assistive tool for the teacher to help students get introduced to and understand basic fraction concepts, the assignments should not be very complex. The difficulty should be in line with the sorts of problems that children would have to solve when first introduced to fractions in primary school. To keep the difficulty in line with the teaching material, online learning material for introductory fractions was referred to during the design process.

FEEDBACK

Regarding feedback, the learning tool needs to communicate clearly to the users when their actions have an effect on the system. The feedback should also exist in a form that synergises and enhances the other design elements, such as the animal feeding narrative and tangible design. Most importantly, interaction needs to be clear and intuitive. It needs to be evident to the users what they can do with the food objects and what happens when they perform actions on them (feed them to an animal). Users also need to get information on the correctness of their answer (did I do it correctly? If not, what went wrong?). The system should not give too much information regarding what went wrong however, as this can lead to information overload and can prevent users from forming their own understandings and solutions.

Following guideline 1 from [9], information should be distributed across multiple modalities to increase working memory capacity. Based on this, different modalities for feedback should be utilized (audible, visual, tactile).

COMPLEXITY

In order to reduce extraneous cognitive load [9] the learning tool should be kept relatively simple and self-contained. The scope of the project should also be considered here, as only limited time and resources were available for the construction of the prototype. Because of this, more complicated features such as the previously discussed animations do not have space within this project.

4.2.2 FEATURES AND POSSIBLE TECHNOLOGIES

Based on the concept and the design considerations we can now establish a list of features that the learning tool should have and subsequent technologies to implement these features.

FEATURES

The features that the learning tool will need to have are the following:

- Tabletop at the right hight for 8 to 10 year olds with enough room for 4 children to stand or sit around it and use the learning tool. The tabletop needs to be distributed into 4 zones that are clearly divided over 4 different animals (cow, pig, sheep, chicken).
- 3 sets of manipulative food objects. The objects need to be as freely manipulatable as possible.
- Some way of detecting which objects are where.
- Assignments of varying difficulty. The assignments need to communicate clearly enough what the users need to do. Users also need to be able to pick the assignment that they want to work on, so the assignments should also have some indication of their difficulty.
- A way of submitting an answer that subsequently communicates to the users whether the answer is correct and gives some information about what went wrong.
- A way of correcting an incorrect answer.
- Multimodal feedback and information distribution.

TECHNOLOGIES FOR OBJECT DETECTION

Out of all different elements of the learning tool, the food objects and their detection are the most crucial. The whole system would not work if it could not be reliably detected when an object is distributed to an animal. At the same time, this needs to not get in the way of the tangibility and manipulability of the food objects.

Because of its importance, the implementation and necessary technologies for object detection had priority over the other features. To solve this design problem, a number of technologies were identified. See table 2 for a list of the considered technologies and their advantages and disadvantages.

Technology	Advantages	Disadvantages
RFID readers and tags	Cheap	Tags can only be detected in a limited area close to the reader (unless much more expensive readers and tags are used)
	Simple to use and program	Reading multiple tags from one reader at the same time is not possible (unless much more expensive and complicated readers and tags are used)
BLE (Bluetooth beacons)	Allow for position determination for each object simultaneously	Each object would require a beacon, so the amount of objects would be very limited to save costs
	Large area for object detection	The beacons require batteries to operate
Computer vision	Objects can be detected from anywhere on the table simultaneously, provided the camera can see them	Children can block the camera view, making it somewhat unreliable
	Large area for object detection	The camera would have to be suspended above the table, complicating the overall design
		More complicated to program

Table 2. 3 technologies considered for object detection and their advantages and disadvantages.

In the end, RFID readers and tags were chosen as the implementation method for object detection, due to the affordability and simplicity of the technology. RFID readers are also relatively easy to integrate into the table top design, not requiring any external elements. Each food object would have a unique tag inside and every animal zone would have a reader for detecting the tags.

The RFID tags and a reader could also be used for the assignments. Each assignment could be written on a card with a RFID tag attached to it. In order to choose an assignment, users would take an assignment and place it in a specified place that has a RFID reader. This way choosing an assignment also becomes a more physical and embodied activity. A predefined position for active assignments also allows users to store information about the task at hand in a clearly defined place in their physical surroundings, potentially serving as cognitive offloading and reducing extraneous cognitive load.

DESIGN LIMITATIONS

The limited detection capacity of the cheaper RFID readers do bring with them some design restrictions. As the detection radius is small, and objects can only be detected one by one, the way in which users provide answers has to be more limited. The animal zones will need specific slots for ‘feeding’ said animal, only allowing for one object to be ‘fed’ at a time. This also means that correcting an incorrect answer requires a more complicated mechanism, as the objects would most likely have to be inaccessible once 'fed'. The limited detection capacity also brings limitations to the size and shape of the food objects.

Fortunately, these limitations are not purely disadvantageous to the design. Forcing users to slow down interaction by only allowing one object to be fed at a time to each animal could provide users time to reflect deeper on what they are doing, which can be beneficial to the learning process [9]. Having the objects be stored in a clearly separate area after being fed could also actually make interaction more clear, creating a clear distinction between the objects that are and the objects that are not counted for the answer.

TECHNOLOGIES FOR OTHER FEATURES

With regards to the other features, there are various modalities in which they can be implemented. Using visual and audible cues can be great for giving feedback and information distribution. Possible technologies could be coloured LED's, engraving or painting icons, and playing sounds through small speakers. Points where users need to interact more directly with the learning tool, such as submitting an answer, correcting an answer or choosing an assignment, could benefit from something more tactile and embodied. For this, various kinds of button mechanisms or gesture detection could be used. The specific ways in which these features were implemented are discussed in later parts of this chapter.

4.3 FINAL DESIGN: FRACTION FARM

Based on the identified considerations, features and core technologies the final version of the concept was created, along with a fitting name: Fraction Farm (or Breuken Boer in Dutch). Before the final design was settled upon, the various elements of Fraction Farm went through multiple iterations and design explorations. Once the design was finalized, it was developed into a physical functional prototype.

Figure 8. The finished prototype of Fraction Farm. See the following sections for a description of each of the elements and their design.

4.3.1 DESCRIPTION OF THE SYSTEM

Fraction Farm is a learning tool which helps children learn fraction concepts through the completion of assignments. These assignments consist of dividing up sets of objects into different zones, framed as dividing up food amongst 4 different farm animals (cows, chickens, pigs and sheep) which are displayed as icons on a round table. As children complete them, the assignments incrementally increase in difficulty. The goal is to answer each assignment correctly, where a correct answer means having the correct amount of each object in each zone.

4.3.2 DESCRIPTION OF COMPONENTS

Within Fraction Farm there are 4 main components: **the assignments**, **the food objects**, **the table** (where most of the interaction happens) and a smaller **side table** (used for storing the objects and assignments and choosing the assignment you want to solve).

ASSIGNMENT CARDS

The assignment cards are the parts of Fraction Farm that contain information about the assignments. Children would pick one card to solve at a time. An assignment card lists all the animals and the fraction of each food object that they need to receive. The assignments can have varying levels of difficulty, with more or less different food objects (between 1 and 3), more or less complicated fractions and more or less total food objects that need to be divided up.

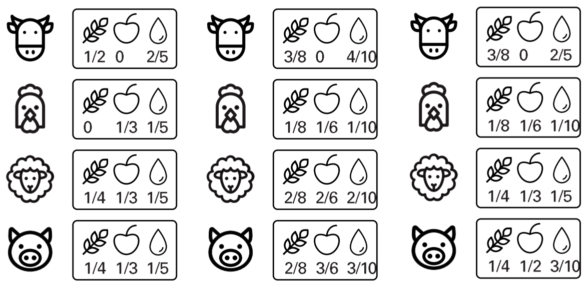


Figure 9. Initial version of the assignment cards displaying 3 different possible assignments.

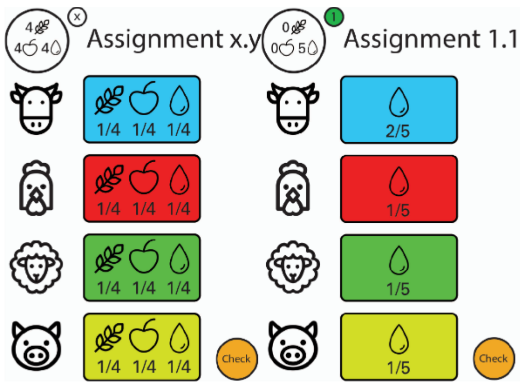


Figure 10. Second iteration of the assignment cards. On the left the template for the assignments, on the right an example of a simple assignment with only the water food type.

The design of the assignment cards went through various iterations. Initially, the cards simply listed all the animal icons together with the fractions for each animal (see figure 9). The following version (see figure 10) also implemented the colours from the table to further help communicate what needed to go where. This version also listed the amount of objects necessary for said assignment on the top left corner. It also could portray the difficulty of the assignment through a number at the top and would have a button for checking the assignment at the bottom.

The final version of the assignment cards (see figure 11) was more simplified, removing the difficulty rating and check button from the card. To further emphasise the farm and animal feeding narrative, the assignments were now framed as separate days on which the animals were to be fed, with the tasks increasing in difficulty each day. This made a separate difficulty rating on the card obsolete. The check button was moved to a part of the table, as having one on each card was unnecessarily complicated.

Difficulty of the assignments was also tuned a bit more to fit what children tend to learn when first introduced to fractions, i.e. distinguishing between numerator and denominator, simple fractions like ½, 1/3, ¼ and simplifying fractions (2/4 = ½). Looking at figure 11, this was implemented by changing the total number of the foods for each day to create a connection between the denominator and the total number of the food type, making the smallest fraction 1/6, and creating a connection between 6ths and 3rds with the 3rd assignment.

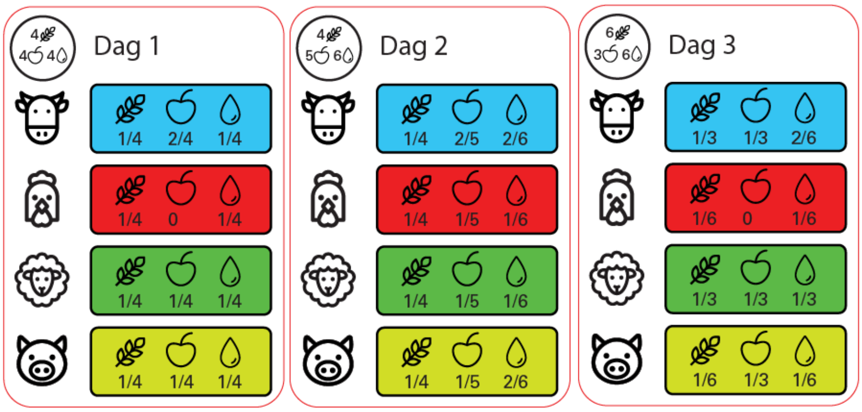


Figure 11. Final version of the assignment cards. The cards are framed as days in which the animals need to be fed, with each day having more complicated fractions and combinations of fractions to solve.

For the prototype, the assignments were printed and engraved onto pieces of thick white plexiglass. This was done to give them some weight and texture, in order to deepen the experience of picking them up and holding them.

Figure 12. The assignment cards built for the prototype

FOOD OBJECTS

The food objects are the manipulative objects that the children need to distribute. They serve as the physical and concrete scaffolding to help establish internal abstract understanding of fraction concepts. As the food objects are the elements of Fraction Farm which are centred around tangible interaction, the way they are designed is significant. However, the shape and design of the food objects was difficult to establish.

Initially the idea was for the physical shape of the objects to carry meaning. They would either look like the foods they were meant to represent, or convene some information relating to the fraction they were meant to represent (for example a 1/3 slice of a pie). This however proved very difficult to design into 3 clearly cohesive sets. The limited detection capacities of the RFID readers and RFID tags, together with the fact that each assignment could require different amounts of each food type were also big limiting factors.

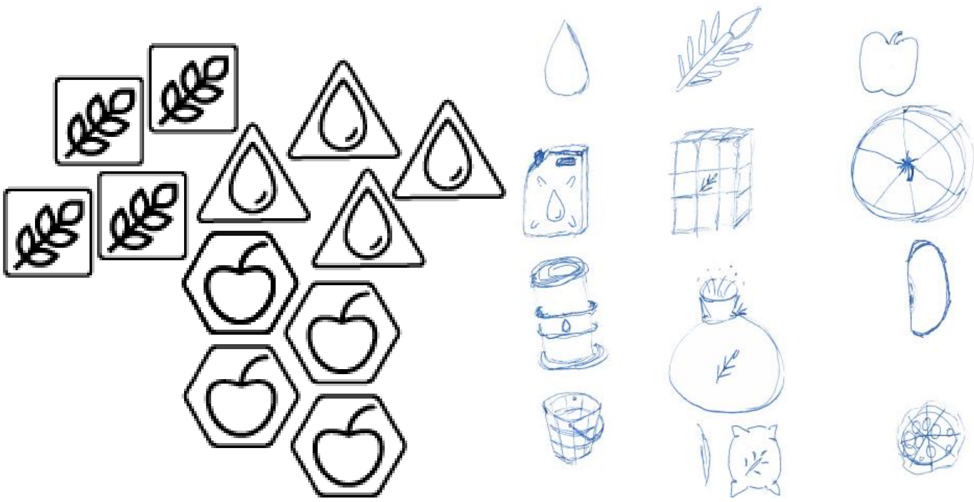


Figure 13. Ideation on the food object design. On the left: a version where the objects are simple geometric shapes. On the right: exploration of designs where the objects look more like the foods themselves instead of just simple icons (i.e. a jerrycan, drum or bucket of water, a sack or bale of grains, a sliced up apple).

In the end, the idea of the shape of the objects carrying significance was rejected in favour of a simple coin design with icons of the food types was. This ensured optimal object detection, while still being clear. Coins are very universal and their simplicity means that they carry very little extraneous information, minimising extraneous cognitive load. The icons on the coins would be slightly inset to allow the information about their food type to be distributed in both a tactile and visible manner, increasing their tangibility.

Figure 14. On the left: 3d model of the final food object coin designs with inset food type icons. On the right: the final 3d printed coins of the prototype

THE TABLE

The table is the core of the system, facilitating most of the interaction and feedback. Throughout the design process, the design of the table stayed fairly constant. The main adjustments that were made concerned the places for depositing objects and how users would pick an assignment to solve.

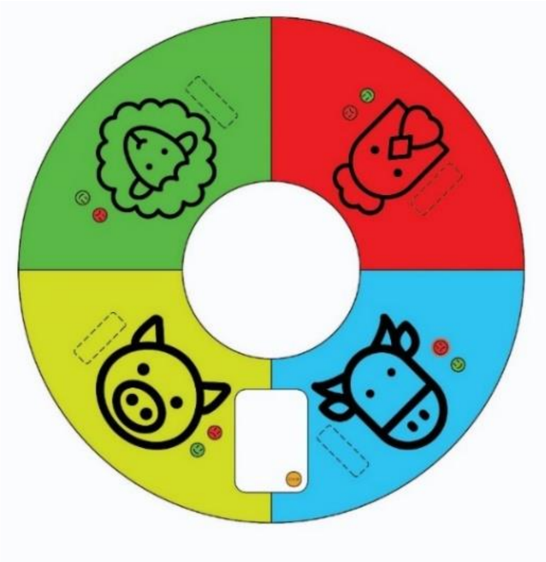


Figure 15. Early version of the table design with the active assignment area on the table and simple object deposit slots next to the animal icons.

Initial designs had a place on the table where children would place the assignment that they would want to solve. This made the design of the table less coherent and more cluttered however. Therefor this feature was moved to a separate smaller side table, which would also house places to store the food objects and inactive assignments.

Figure 16 shows the final concept of the table, which is divided into several areas:

- The Object Origin in the centre of the table. Here all the food objects necessary for the current assignment should be put at the start of said assignment.
- The animal areas. These consist of 4 different areas (‘pens’ or ‘enclosures’), each belonging to a different farm animal (cow, chicken, pig and sheep).
- Each area has its own Object Deposit where users can insert the necessary food objects to correctly complete the assignment. The top of the deposit is transparent, allowing users to see what is stored. Whenever a food object is inserted, a yellow light next to the Deposit will blink and turn on. The food objects inside a Deposit cannot be accessed until the red button next to the Deposit is pressed. When the button is pressed, all the objects in the Deposit will be ejected, no longer counting them for that animal, and the yellow light will turn off.
- Next to each of the animal icons there are 2 icons, a green happy smiley and a red sad smiley, indicating whether said animal has the correct amount of each food object. When users check whether the assignment is correct, either the sad or happy smiley will light up, depending on if a correct or incorrect amount was inside the Object Deposit.

All the icons on the table would be engraved into the tabletop, making them more tactile similar to the icons on food object coins.

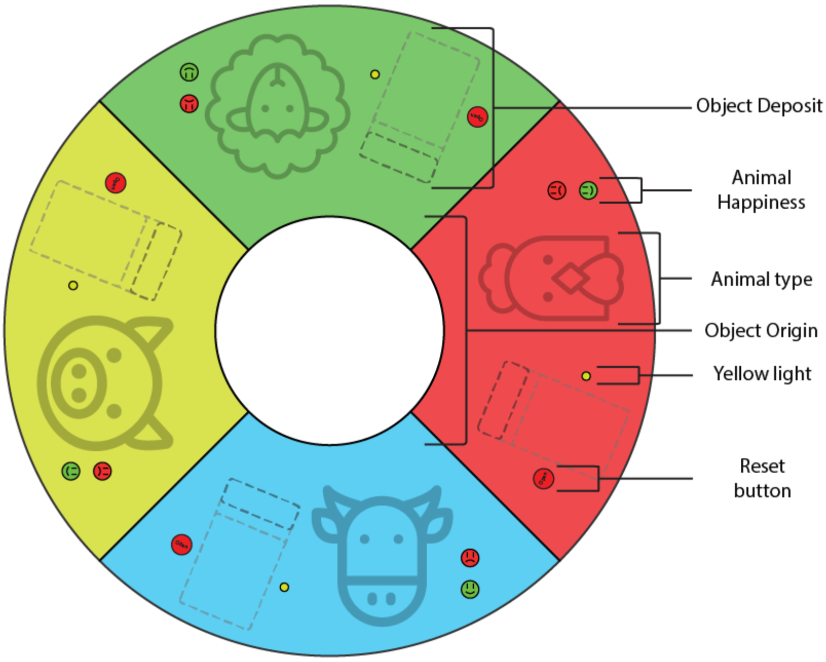


Figure 16. Final concept of the Fraction Farm table

The design of the object deposits had to take into account the limitations of the RFID technology as described in previous parts. Originally they would simply consist of a slot that users could drop the food objects into. An RFID reader would be embedded into the side of the slot, detecting objects as they moved past. This design was very simple however, and did not consider how users would remove objects from the slots, or how users would gain information about what was currently stored in the deposit.

For the final concept, a more refined design for the object deposit and its mechanics was made. After being inserted, the objects would be held in an area under the table. The top of this area would be transparent, allowing users to see what has been inserted into the deposit. Next to the deposit would be a button that users could press to empty the deposit, ejecting all the stored objects into another holding area under the table.

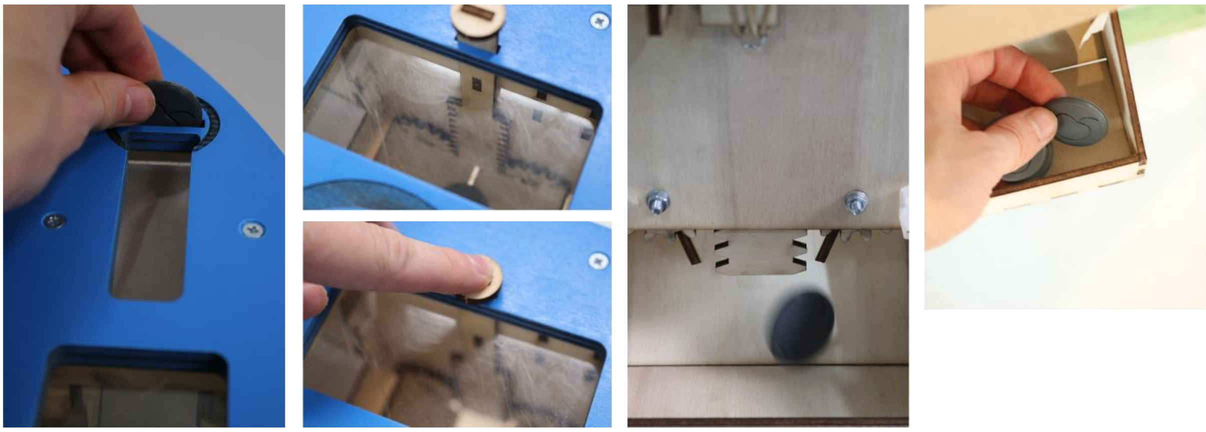


Figure 17. The object deposits on the prototype. Pressing the button empties the deposit, allowing the ejected objects to be picked up from a separate holding area under the table.

On the prototype, the object deposits ended up taking a bit more space than designed. Because of this they were moved further to the edge of the table. The slots for inserting the food objects also got some engraved icons above them, indicating that the food objects had to be inserted there.

Figure 18. The food deposits on the prototype table. On the right above the object insertion slot there are the food objects with an arrow pointing to the slot. All the icons on the table are engraved into the table top.

THE SIDE TABLE

The final part of the system is the side table. This component serves as both a storage for the food objects and assignments, as well as the place where users can pick assignments and check their answers. It consists of a couple area's:

- The Object Storage. Here all the food objects are stored while they are not used for an assignment.
- The Assignment Storage. Here all the assignment cards are stored while they are not used.
- The Active Assignment. Here users can place an assignment card. The card currently placed in the assignment zone is the one the system will check for. Users can check whether the assignment was completed correctly by pressing a button at

the bottom of the assignment zone. If the assignment was completed correctly, the assignment zone will light up in green after pressing the button. In case of an incorrect answer, the zone will light up in red instead.

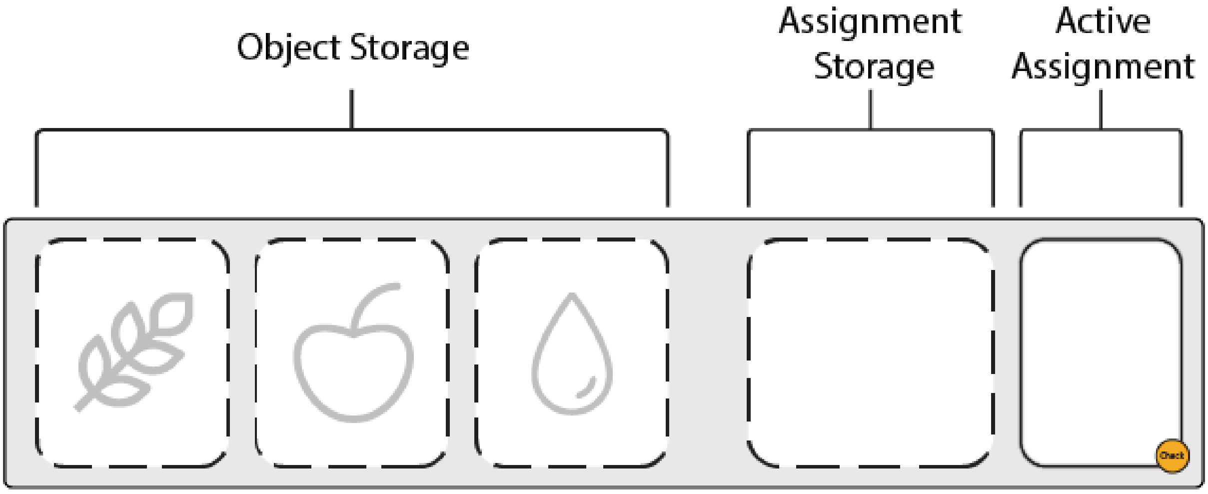


Figure 19. Design of the side table

Having the separate side table act as a hub for the objects and assignments was also done to slow down interaction and promote reflection. The Tangible Learning Design Framework [9] describes slowing down interaction to be potentially beneficial for learning, as it can stimulate reflection. Forcing the children to move away from the main table at the start of an assignment to pick a new assignment and take all the necessary objects for said assignment could act as moment of reflection on the to be solved assignment. Similarly, children will have to step away from the main table to look at the active assignment, which could also act as a moment of reflection.

Figure 20. The side table constructed as part of the prototype

On the prototype a lid for the assignment cards was introduced. This was done as having the unused assignments visible was distracting from the active assignment. Instead of a light strip surrounding the active assignment zone, there were now 2 coloured LED’s (green and red, similar to the happy and sad smiley LED’s on the table) for indicating whether or not the assignment was completed correctly. Finally, a yellow LED above the active assignment was implemented, indicating whether an assignment was active or changed. With no assignment active, the LED would be off. Whenever a new assignment was put in the zone, the light would blink and turn on, indicating that a (new) assignment was active.

4.3.3 OPERATION OF THE SYSTEM

The following part describes how Fraction Farm is used and how the system gives feedback and interacts with its users. Figure 21 and 22 on the next page show diagrams of Fraction Farm's operation, followed by the steps users would take when using the system as described by the numbers on figure 21.

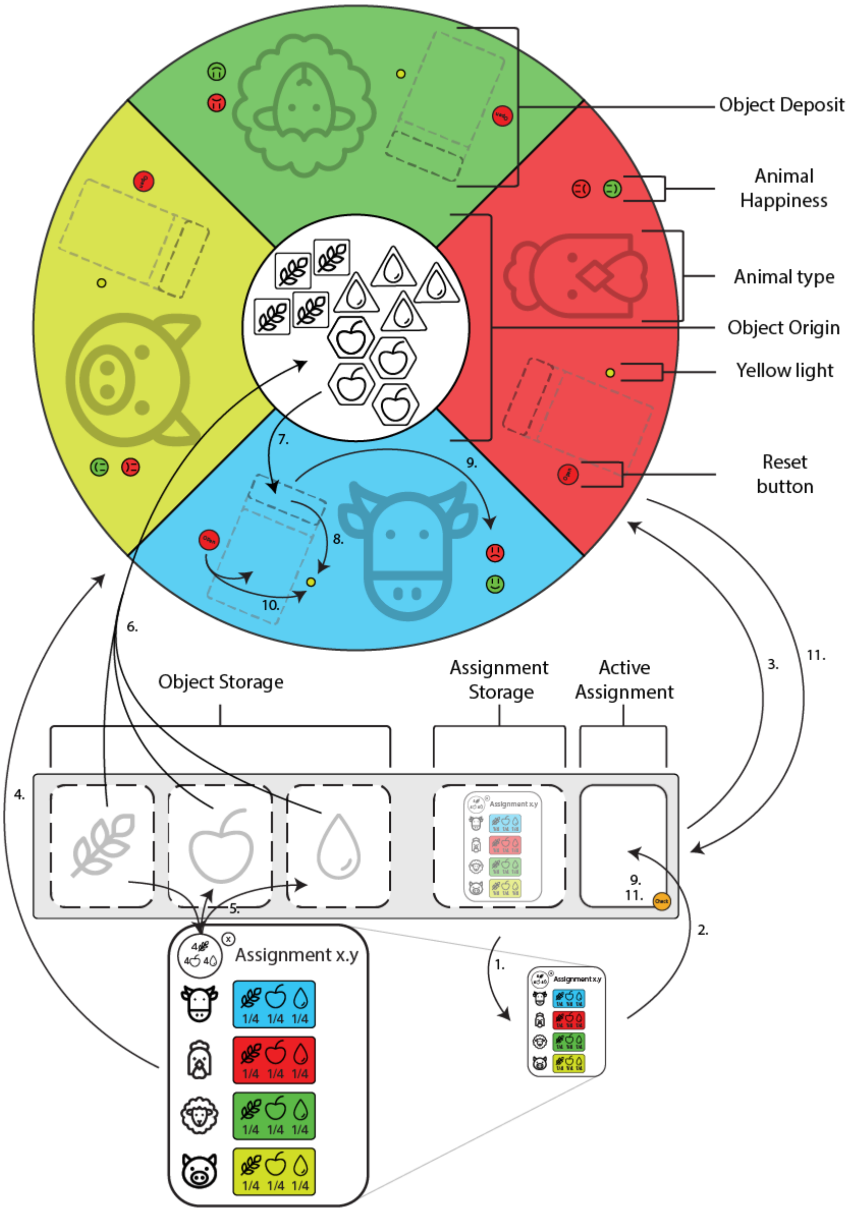


Figure 21. Diagram of the operation of Fraction Farm. The numbers in the diagram correspond to the steps described in the following parts.

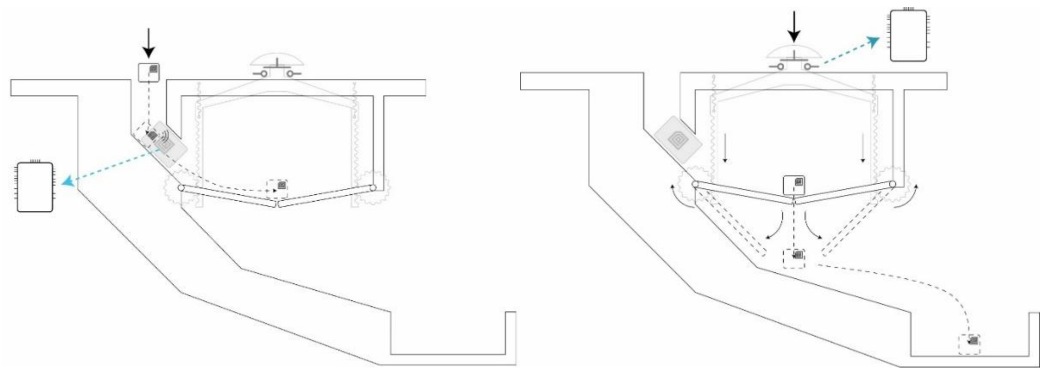
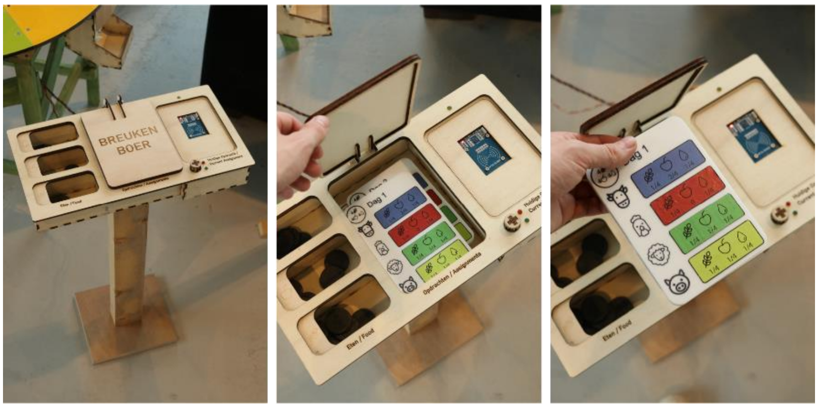


Figure 22. Schematic of how the object deposit works. On the left it shows how an object would be deposited, being detected by an RFID reader as it slides into the deposit. On the right it shows how the deposit is reset by pressing the button, ejecting its contents into another holding area below it.

1. In order to begin, users can take an Assignment Card from the Assignment Storage

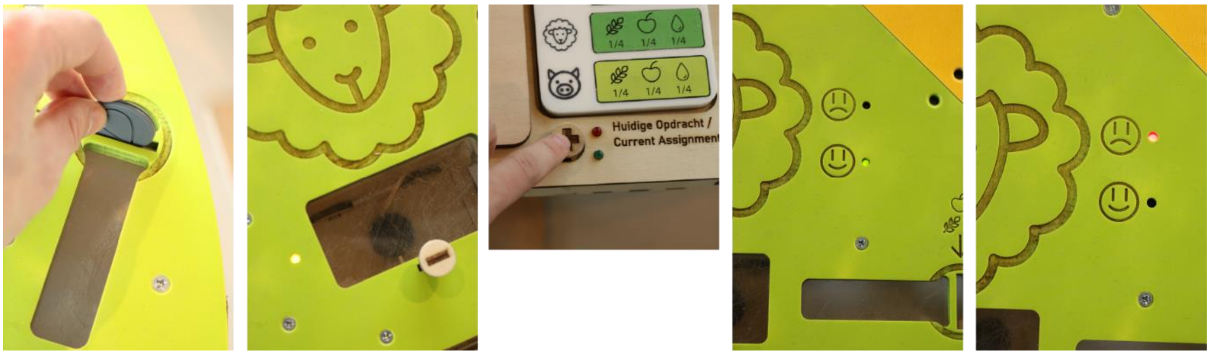


2. The chosen assignment card can then be placed in the Active Assignment zone
3. An RFID reader in the Active Assignment Zone reads an RFID tag in the Assignment Card, informing the table which amount of which object to count as a correct answer for each zone and making the LED above the assignment blink and turn on
4. Based on the information next to each animal on the assignment card, users can read how they are supposed to divide the objects
5. The symbols in the top left corner of the assignment card indicate how many of each object type are needed for that assignment

6. Users can take the needed objects from the Object Storage and place them in the Object Origin

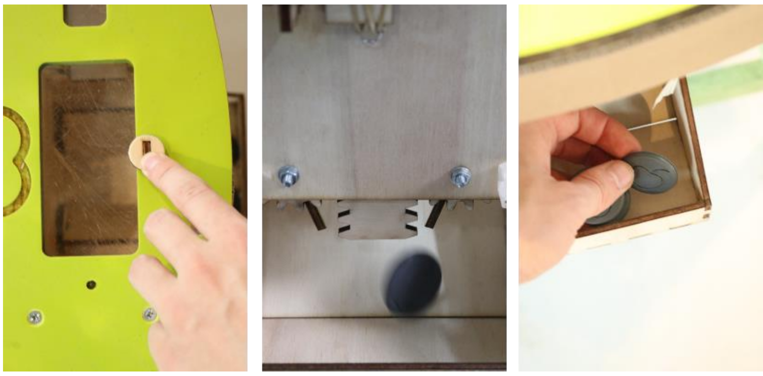
- Users can now begin with the assignment

7. Once users have figured out which objects belong with each animal, they can submit their answer by inserting the objects belonging to each animal into the Object Deposit of each animal
8. When objects are deposited, the yellow light next to that Object Deposit will blink and turn on, indicating that objects are being counted.
9. When the check button is pressed, a light next to the animal will light up; sad or happy depending on whether that animal got the correct amount of each object on the active Assignment Card

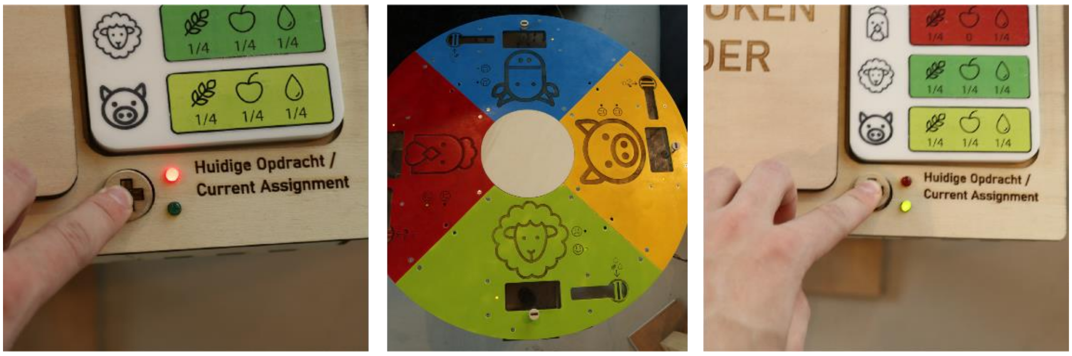


10. When users want to remove objects from the object storage (either because they gave an incorrect answer or want to start a new assignment), they can press the

button next to the Object Deposit, which ejects all the objects it was holding, resets the count for that zone and turns off the light next to the deposit.



11. If all the animals got the correct amount of each object in their deposit when the check button is pressed, a green LED under the active assignment will turn on. If the assignment was not completed correctly a red LED will turn on instead.



INPUT AND FEEDBACK

The information input and output of the Fraction Farm system is described in figure 23. Users interact with the system through the RFID readers in the active assignment zone and object deposits as well the check and reset buttons. The system gives feedback based on which assignment is being read by the active assignment zone and which objects were inserted to each animal. Feedback is given to the users through the happy / sad LED's, the LED's at the active assignment zone and the yellow LED next to the object storage.

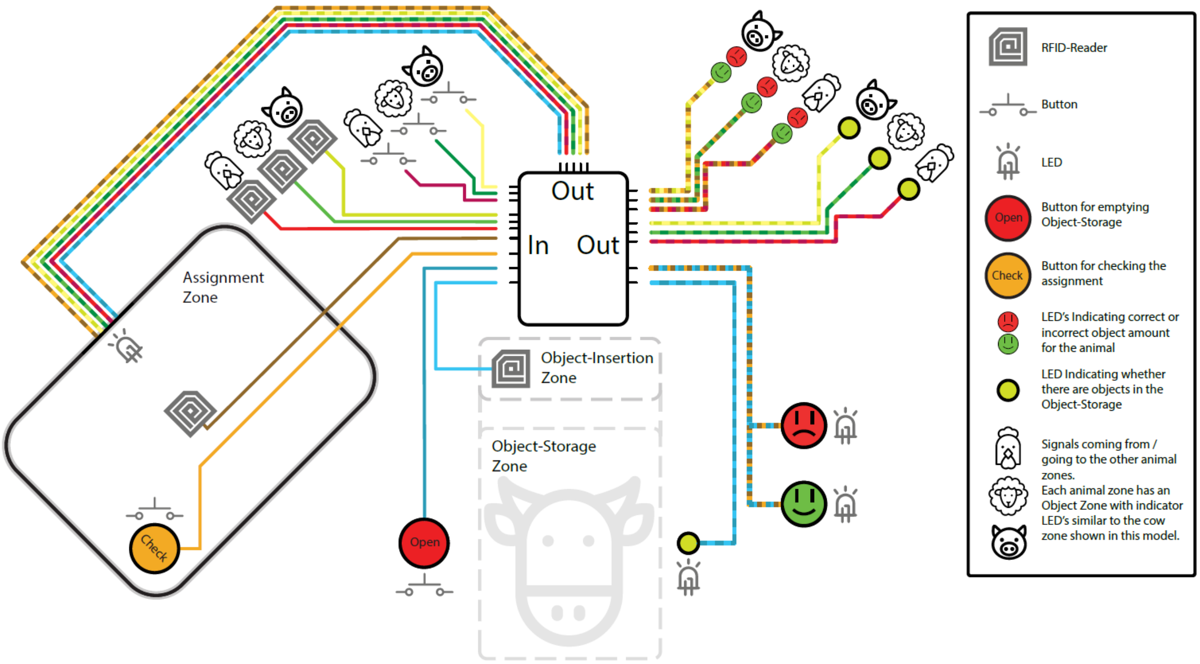


Figure 23. Information input and output diagram.

4.3.4 IMPLEMENTATION OF THE TANGIBLE LEARNING DESIGN FRAMEWORK

The Tangible Learning Design Framework by Antle and Wise [9] was utilised throughout the design process. An overview of how all the guidelines were implemented into the final Fraction Farm design can be seen in table 3.

Perspective	Guidelines	Implementation
Info processing	1. Distributing information across modalities can increase effective working memory capacity	Feedback through lights; Information communicated through visible and tactile (engraved) icons; Freely manipulatable / distributable objects allow for information distribution
	2. Making mappings between the form and behaviour of physical and/or digital objects and real-world entities coherent can reduce extraneous cognitive load	The objects represent foods; The various zones for the food objects represent animals that would consume said foods
Constructivist	3. Creating authentic tasks and using personal objects can support learners in forming individually meaningful goals for interacting with the TUI	Framing the assignments as resource management of food for animals; making the animals happy when the assignment is completed correctly
	4. Using spatial, physical, temporal or relational properties can slow down interaction and trigger reflection	The food slots only allow for one food object to be inserted at a time; Users have to manually take a new assignment card out of the assignment storage and place it into the assignment zone to start a new assignment
Embodied	5. Distributing parts of mental operations to actions on physical and/or digital objects can simplify and support mental skills	Information communicated through visible and tactile (engraved) icons; Freely manipulatable / distributable objects allow users to create tangible and visual representations of the fractions they have to create
	6. Leveraging image schemas in input actions can improve usability and system learnability	Inserting objects counts them, removing them removes them from the count (in- out image schema)
	7. Using conceptual metaphor(s) based on image schemas to structure interaction mappings may bootstrap learning of abstract concepts	The food objects of a specific type are all clearly connected in such a way that the objects together create either one clear set or one complete object (part of a whole / set image schema). This bridges to the abstract concept of fractions, as the mathematical description "1/4" can be physically represented as one object belonging to a set of four or one part of a whole object split in four pieces.
Distributed	8. Designing objects that allow spatial reconfiguration can enable mutual adaptation of ideas	Freely manipulatable / distributable objects allow for spatial reconfiguration
	9. Using concrete representations can support interpretation of symbolic representations of abstract concepts	The food objects of a specific type are all clearly connected, both physically (same shape), visually (same icon) and as a metaphor (grain, fruit or water for the animals to consume). This way the mathematical description "1/4 of the grain" written on the assignment card is physically represented as one grain object belonging to a set of four / one part of a grain object split in four pieces as well as a metaphor as one fourth of the available grain.
Collaborative	10. Creating configurations in which participants can monitor each other's activity and gaze can support the development of shared understandings	The table is deliberately round and flat, making it easy for participants to monitor each other's activity at the table
	11. Distributing roles, information and controls across the TUI learning environment can promote negotiation and collaboration	The layout of the table suggests distributing users over the 4 different zones
	12. Creating constrained or co-dependent access points schemes can compel learners to negotiate with each other	The object insertion slots for the different zones are fairly far away from each other, promoting interaction with multiple users

Table 3. Overview of the implementation of the Tangible Learning Design Framework [9] in the final Fraction Farm design.

4.4 IMPLEMENTATION

The following section describes how Fraction Farm operates on a more technical level and how the prototype was constructed.

4.4.1 MICROCONTROLLER IMPLEMENTATION

The Fraction Farm system is ran by 3 Arduinos (2 Arduino NANO's and 1 UNO). Detection of the food objects and assignments was done using MFRC522 RFID readers and compatible RFID tags on the objects and assignments. Using 3 Arduinos instead of just one was necessary, as having 5 of the MFRC522 RFID readers running simultaneously on one Arduino made the detection of tags too slow and therefor too unreliable (70-80% of inserted tags instead of ~95% with just 1 or 2 readers). This could be due to the Arduino's inability to run parallel operations, allowing it to only interpret data from one reader at a time. Using microcontrollers with more processing power, such as the ESP8266, also did not solve the issue. In the end using 3 microcontrollers proved not to be a big obstacle, as the overall system remained fairly simple.

The 3 Arduinos communicate using I2C, with 1 Arduino (the UNO) acting as the master and the other 2 (the NANO's) acting as slaves. The slave Arduinos are each in charge of 2 animal zones, keeping track of which objects are stored for each animal and sending that data to the master Arduino. The master Arduino is in charge of keeping track of the active assignment, the total count of all the objects in each zone and whether or not the counts in each zone are correct based on the active assignment.

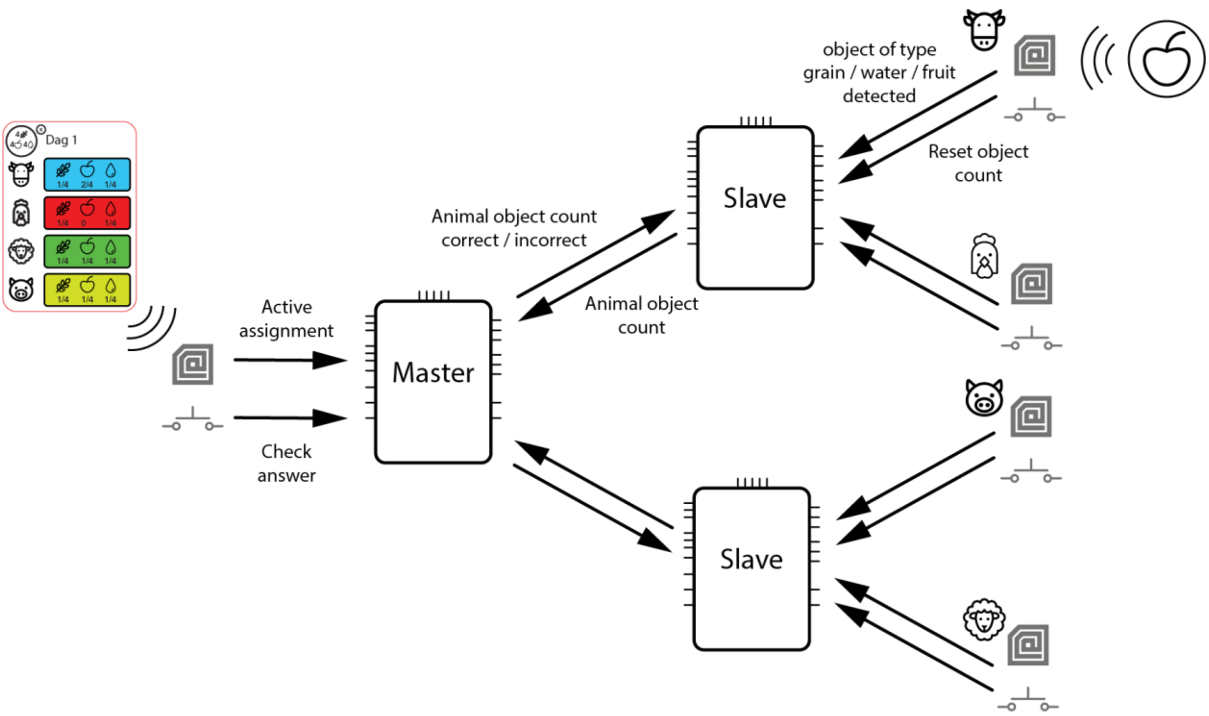


Figure 24. Diagram of the communication structure of the Arduinos.

All the objects and assignments contain RFID tags with unique ID codes. Each Arduino has a list in their memory of which ID corresponds to which food type (for the slave Arduinos) or assignment (for the master Arduino). Whenever any of the readers detect a tag, they send the ID of the tag to the corresponding Arduino, which will then match it with the corresponding food type or assignment. See figure 24 for an overview of the communication structure.

Whenever the check answer button is pressed, the master Arduino checks whether the count of all the objects in each zone corresponds with the correct answer. It then tells the slave Arduinos which zones had a correct or incorrect answer, and turns either the red or green LED on the side table on based on if the overall answer was correct. When the slave Arduinos are told which zone had a correct or incorrect answer they also turn on the corresponding red (sad) or green (happy) LED's. When the master Arduino detects a new assignment, it turns on the yellow LED above the active assignment (if it was not already on) and makes the LED blink a couple times. Similarly, when any of the slave Arduinos detect an inserted object, they will turn on and blink the yellow LED above the corresponding object deposit, and turn the LED off when the reset button is pressed.

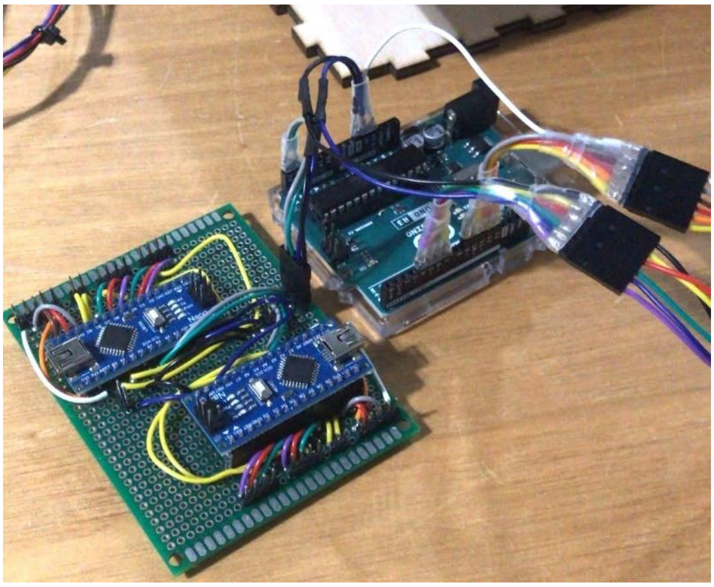


Figure 25. The 3 Arduinos, the 2 NANO's attached to the PCB on the left hooked up to the UNO on the right. The wires on the right lead to the button, RFID reader and LED's on the side table. The NANO's were hooked up in a similar fashion to their buttons, RFID readers and LED's on the main table.

4.4.2 OBJECT DEPOSIT IMPLEMENTATION

Implementing the object deposits was the most crucial part of the construction of the Fraction Farm prototype. The physical design of the deposits had to overcome the limited detection capacity of the MFRC522 RFID readers. The readers only have a detection range of a couple centimetres, and require a tag to remain in the detection range for a certain amount of time to successfully read data from the tag. This meant that the design of the deposits had to ensure that inserted objects passed by the readers slowly and with close proximity. As such, the objects could not simply be dropped past the readers, but instead had to slide past the reader in a relatively controlled manner.

Various prototypes of the deposit were made to test the at which slope angle, drop distance and reader position the objects would be detected optimally. The material of the slope on which the objects would slide also mattered, rough surfaces providing too much friction thus preventing the objects from sliding properly.

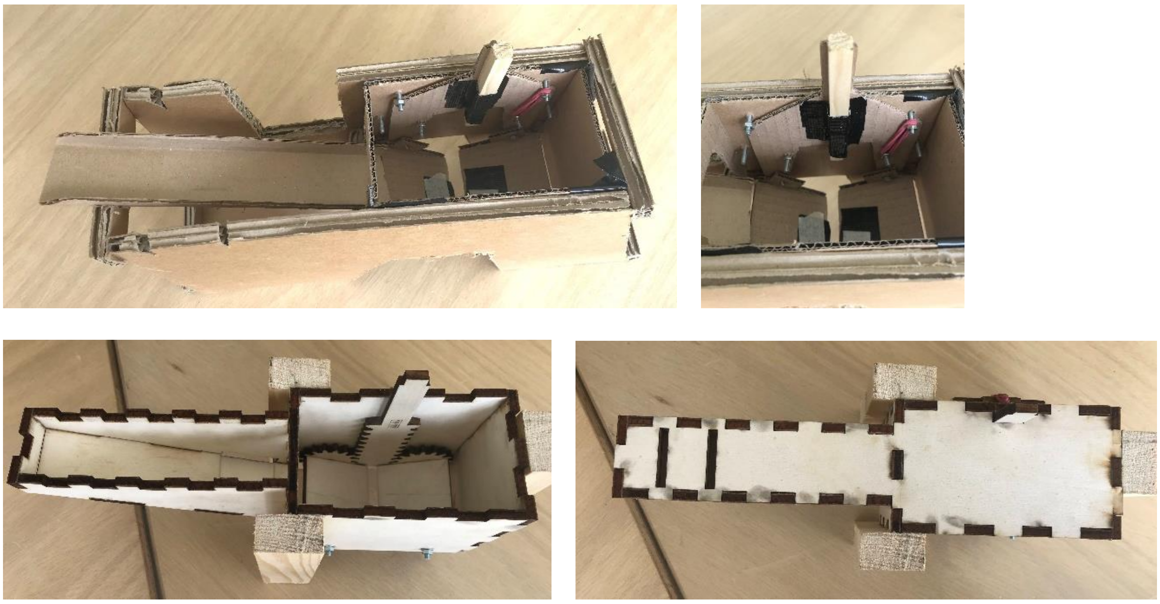


Figure 26. Early cardboard prototype for testing slope angle and reader position (above) and lasercut wooden prototype (below) for testing 2 different slots where the objects could be inserted.

The deposits also needed to be able to store objects, and eject them when a button was pressed. To keep the system simple, no motors were used for this. Instead, the movement of pushing the button was also utilized for ejecting the stored objects. The button was mechanically linked to 2 flaps at the bottom of the deposit, such that whenever the button was pressed, the flaps would open and all stored objects would drop out. Rubber bands attached to the mechanism would pull the button back up, closing the flaps and also providing some tactile resistance to pressing the button.

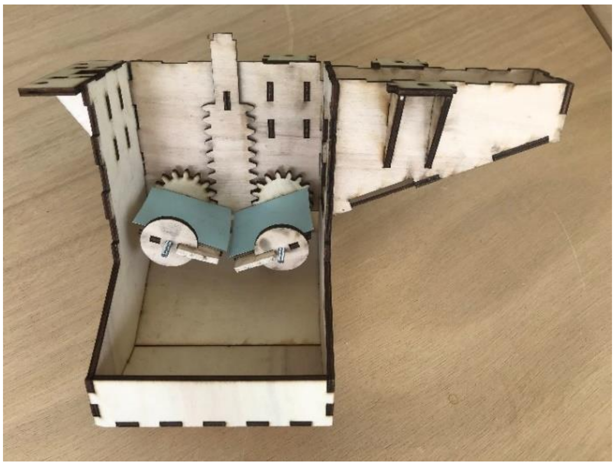


Figure 27. Final version of the deposit design, showcasing the coupling between the button and the 2 flaps using a gear and rack mechanism.

The pressing of the buttons also had to be electronically detected, so that the system would know when objects were no longer being stored. This was done by attaching a small magnet to the button mechanism. Whenever the button was pressed deep enough to eject all the objects, the magnet would pass by a Hall effect sensor which would detect the magnetic field, sending a signal to the connected Arduino (see figure 28). The check button on the side table also works in the same way using a magnet and hall sensor.

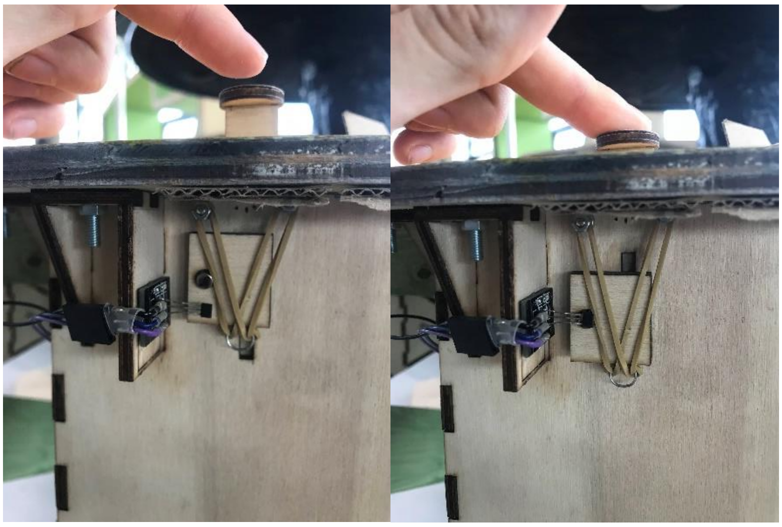


Figure 28. Detection of the button being pressed using a magnet and a hall sensor and the rubber band pulling the button back.

4.4.3 CONSTRUCTION OF THE PROTOTYPE

The final prototype of Fraction Farm was largely constructed from parts lasercut out of wood and plexiglass. A table base of appropriate height for children aged 7 to 10 was manually cut and constructed to which all the lasercut parts were then attached. The lasercut parts for the tabletop were designed such that the object deposits could easily be attached. Most of the electronics and microcontrollers were attached to the bottom of the table top, with some longer wires linking up the electronics of the side table.

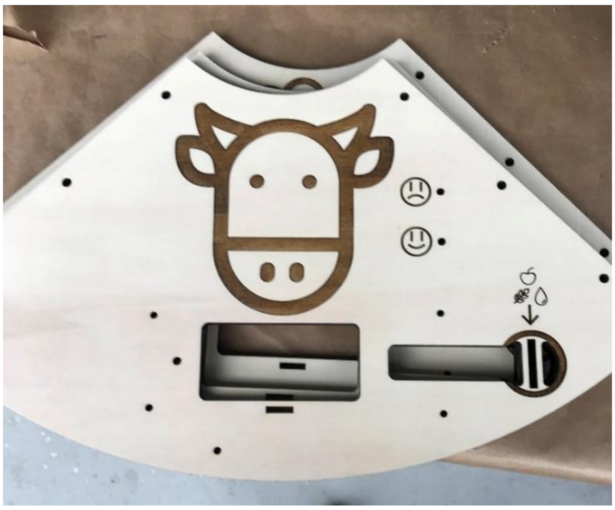


Figure 29. The lasercut animal zone parts. The holes on the sides allowed the parts to be easily attached to the table base using screws. Similarly, the holes at the bottom allowed the object deposits to be attached to the animal zone parts.

CHAPTER 5. EVALUATION

In order to evaluate the design choices of Fraction Farm in a practical setting, a user study was conducted. The goal of the user study is evaluating the enjoyability of using Fraction Farm and all of its components, and to what extent the design choices described in the previous chapters successfully lead to tangible interaction and collaboration. This was done by observing how children interacted and solved increasingly difficult assignments with the prototype, and collecting their reported experiences. Exposure to the prototype, the length of exposure to the prototype and the difficulty of the assignments served as the independent variables. 5 dependent variables regarding user experience and tangible learning design were identified, along with measures and methods.

5.1 DEPENDENT VARIABLES

The dependent variables are **engagement, endurability, expectations, collaboration** and **embodied** activity.

5.1.1 ENGAGEMENT, ENDURABILITY AND EXPECTATIONS

The first 3 variables pertain to the fun and enjoyability of using the prototype. Evaluating the fun and enjoyability of the prototype is important, as a poor user experience gets in the way of tangible interaction. In order for meaningful tangible interactions to take place, users need to be engaged physically and mentally. If the prototype is too difficult or not enjoyable to use, users will not be motivated to explore and interact with the prototype.

As user experience can be tricky to evaluate with children, the toolkit for measuring children's fun by [13] was used to establish variables and measures. While fun is not a usability metric, it is parallel to usability. As systems designed for children cannot be evaluated on the same terms as more standard work systems, measuring fun is a great way to get insight into user experience [13]. The user experience variables for measuring fun are **engagement, endurability and expectations,** identified by Read et. al. and utilized in the toolkit [13]. **Engagement** concerns the extent to which participants are engaged with the prototype. **Endurability** is defined in 2 parts by [13]; **remembrance**, *"our likelihood to remember things that we have enjoyed"*, and **returnance,** *"the desire to do again an activity that has been fun.".* Regarding **expectations**: *"The term expectation is used in this context to describe the fun that is attached to an event, and the fun as it is affected by the prior expectations of the user."* [13]. [13] describes various tools and observable behaviours that can be used to measure these variables. A number of these were implemented for this study, as described in a later part of this chapter.

5.1.2 COLLABORATION AND EMBODIED ACTIVITY

The other 2 variables pertain to tangible learning design. These variables are **collaboration** and **embodied activity**.

Collaboration concerns how and how much users interact with each other when using the prototype. The Tangible Learning Design Framework [9] gives a more narrow definition, with emphasis on negotiation and between users and the construction of a shared conception of the problem. In this definition it is distinguished from cooperation: *"Collaboration differs from cooperative activities. In the latter, learners may coordinate their efforts in that the work* *performed is primarily individual, for example, a divide-and-conquer strategy"* [9]. However, for the purposes of this study, data concerning collaboration was collected in a more broad sense, to also get a more general view of how multiple users interact with each other from a user experience perspective. The definition given by [9] was used to more specifically evaluate the results through the Tangible Learning Design Framework.

Embodied activity concerns behaviours that could be indicative of underlying embodied engagement. As the prototype is designed with physical interaction in mind, simply measuring physical interaction is not sufficient to get a sense of the presence of embodiment. Therefor we define embodied activity through a more specific category of actions. As one of the central themes of their CTI framework, [14] also describes the types of physical actions related to embodied interaction. It makes a distinction between **pragmatic actions,** physical actions directly linked to accomplishing a task, and **epistemic actions**, physical actions aimed at reframing underlying cognitive processes, often utilizing the environment as a scaffold for difficult cognitive tasks. For this study, embodied activity was defined as the presence of epistemic actions. As we cannot gain direct access to internal cognitive processes, epistemic actions can only be observed externally. When it comes to the prototype, examples of epistemic actions could be creating physical representations of fractions using the coins, or arranging the coins according to food type. Later parts of this chapter describe more example behaviours used for quantifying observations regarding embodied activity.

5.2 METHODOLOGY

For this study, 11 participants were recruited, aged 6 to 8, from the local day-care BSO De Vlinder. Due to time constraints however, only 8 participants were able to partake in the study. The study took place at the day-care, in a small room separate from the other children. The user study followed a within-group design, where 4 participants got to interact simultaneously with the prototype for 30 minutes. During this, the participants were tasked with solving 3 assignments of increasing difficulty. Each participant got assigned 1 of the 4 animals to work on during the session. After interacting with the prototype, participants were tasked with answering questions regarding fun / usability. Before conducting the study, the study plan was evaluated and cleared by the EEMCS ethical committee of the University of Twente.

5.2.1 OBSERVATIONS

Data was collected through observations during the interactions and the various interview questions after the interactions. The observations were focussed on quantifying and identifying signs of engagement, collaboration and embodied action (see table y), whereas the interview / questionnaire questions aimed at measuring participants' endurability and expectations regarding use of the prototype. As reliably observing 4 participants simultaneously is nigh impossible, 2 observers were present during each session. Each observer focused on 2 participants per session. In order to observe the participants' expressions and actions clearly, the observers positioned themselves across from the 2 participants they were observing.

Figure 30. The observation set-up. Each animal zone would have a child sitting / standing in front of it. Observer 1 would sit facing the participants assigned to the sheep and chicken (see left image for their point of view), observer 2 would sit facing the participants assigned to the cow and pig (see right image for their point of view).

To assist the observation process and the quantification of the observational data, an observation sheet was used (see Appendix). This sheet contained a list of observable behaviours signifying either engagement, collaboration or embodied actions [9], [13], [14] [15] as listed in table 4. This allowed the observers to quickly note down if and how many times certain behaviours took place. See table y for the behaviours related to each variable and related literature.

Variable	Behaviour	Reference
Signs of engagement	Smiles / laughing	[13], [15]
	Concentration signs (fingers in mouth, tongue out)	
	Excitable bouncing	
	Positive vocalization	
Signs of disengagement	Frowns	[13], [15]
	Signs of boredom (ear playing, fiddling)	
	Shrugs	
	Negative vocalization	
Signs of collaboration	Asking others for help / talking to others	[9], [14]
	Peeking at others' work	
	Helping others	
	Joining efforts on one task	
Signs of embodied action	Arranging objects by the animal they belong to (before insertion)	[9], [14], [8]
	Arranging objects by type	
	Dividing objects between participants	
	Arranging physical representations of fractions using the objects	
	Exploration signs;	

	Grabbing, looking, rotating, comparing, etc.	

Table 4. Table containing the categorised behaviours used in the observation sheet

5.2.2 INTERVIEW QUESTIONS

The data collection methods after interaction with the prototype were largely based on the toolkit by [13]. In order to measure endurability and expectations, 4 tools from this toolkit were utilized (see Appendix for the interview materials).

The first question was aimed at measuring expectations through the participants reported experience. It consisted of 2 Smiley-o-Meters [13] (Likert-esque scale utilizing increasingly happy smileys, see figure 31). The first one asked *"How fun was Fraction Farm?"*, the second one *"How fun was solving assignments with Fraction Farm?".* Participants answered by circling the smiley corresponding to their answer.

Secondly the participants were handed an Again-Again table [13], aimed at measuring returnance. The table consisted of a column with 7 activities on the prototype, and 3 columns headed as "yes", "maybe" and "no". By ticking one of these 3 boxes for each activity, participants answered whether they (perhaps) wanted to perform an activity again. See figure 32 for an example.

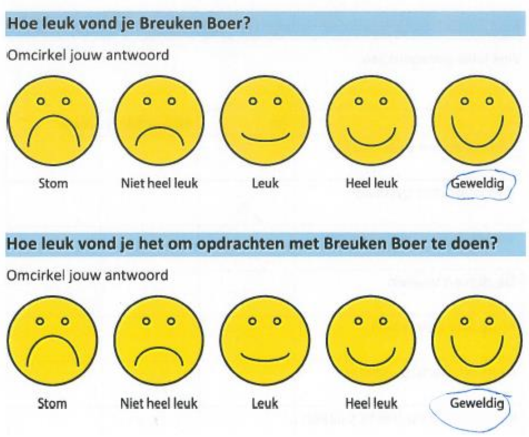
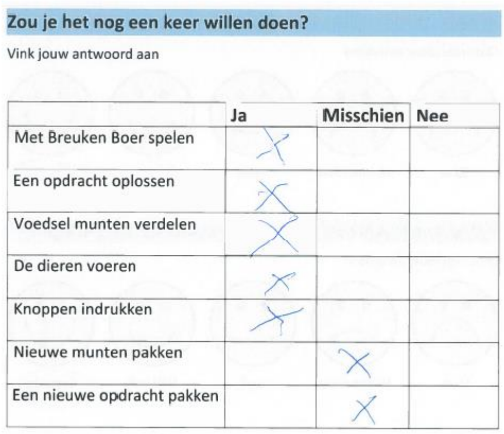


Figure 31. Example of a completed Smiley-o-Meter



Zou je het nog een keer willen doen?

Vink jouw antwoord aan

	Ja	Misschien	Nee
Met Breuken Boer spelen	X		
Een opdracht oplossen	X		
Voedsel munten verdelen	X		
De dieren voeren	X		
Knoppen indrukken	X		
Nieuwe munten pakken		X	
Een nieuwe opdracht pakken		X	

Figure 32. Example of a completed Again-Again table

Third the participants had to complete a card sorting activity, based on the "Fun Sorter" [13]. The participants were each given 7 cards depicting elements of the prototype, and were tasked with sorting them from left to right from least to most fun. This aimed to measure both the participants reported experience as well as their remembrance regarding the different design elements. See figure 30 for an example of a completed card sorting.

Figure 33. Example of a completed card sorting activity

Finally, the participants were handed a blank sheet of paper with the question *"What did we do? (Write / Draw / Tell)"* [13] (see figure 34 for examples of completed sheets). Here the participants were asked to recount what they had done with the prototype. This was aimed at measuring their remembrance. For additional feedback, a sheet of paper with *"How would you improve Fraction Farm? (Write / Draw / Tell)"* at the top was handed to the participants. For an overview of all the variables, measures, methods and materials, see table 5.

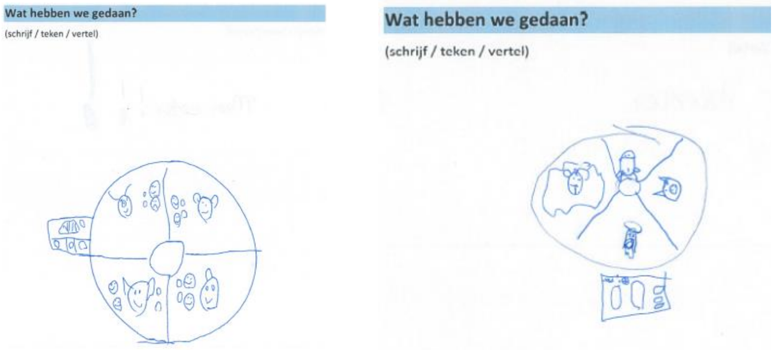


Figure 34. Example of 2 completed 'What did we do?' sheets

Variable	Measure	Method	Materials
Engagement	Signs of (dis)engagement	Observation	Observation sheet
Endurability	Remembrance	What did we do?	Blank sheet of paper, with "describe what you did (write/draw/tell)" written at the top
		Card Sorting	7 cards each describing a different element of the prototype. Participants sort them from least- to most fun.
	Returnance	Again-Again table	Table listing 7 activities with the prototype in one column, and 3 columns containing 'yes', 'maybe', 'no'. Participants evaluate which activity they would like to do again by ticking one of these 3 answers.

Expectations	Reported experience	Smiley-o-meter	Questionnaire with questions pertaining to how they enjoyed using the prototype. Participants answer by ticking 1 out of 5 smileys which most matches their experience.
		Card Sorting	7 cards each describing a different element of the prototype. Participants sort them from least- to most fun.
Collaboration	Signs of collaboration	Observation	Observation sheet
Embodied activity	Signs of embodied interaction	Observation	Observation sheet

Table 5. The dependent variables and the methods for measuring them

5.3 RESULTS

5.3.1 QUANTITATIVE RESULTS

Out of the 8 participants, only 5-6 answered the interview questions. As the sample size of this study was so small, real statistically significant conclusions cannot be drawn. However, the results do give some validation to the design, as well as give points of improvement for future research and design.

EXPECTATIONS

When asked how fun Fraction Farm was, all the participants who filled in the Smiley-o-Meter answered “Brilliant” (the highest level of fun on the scale). When asked about the more ‘academic’ and task-oriented aspect of the prototype, 2 of the participants gave a lower rating than for the first question (see figure 35).

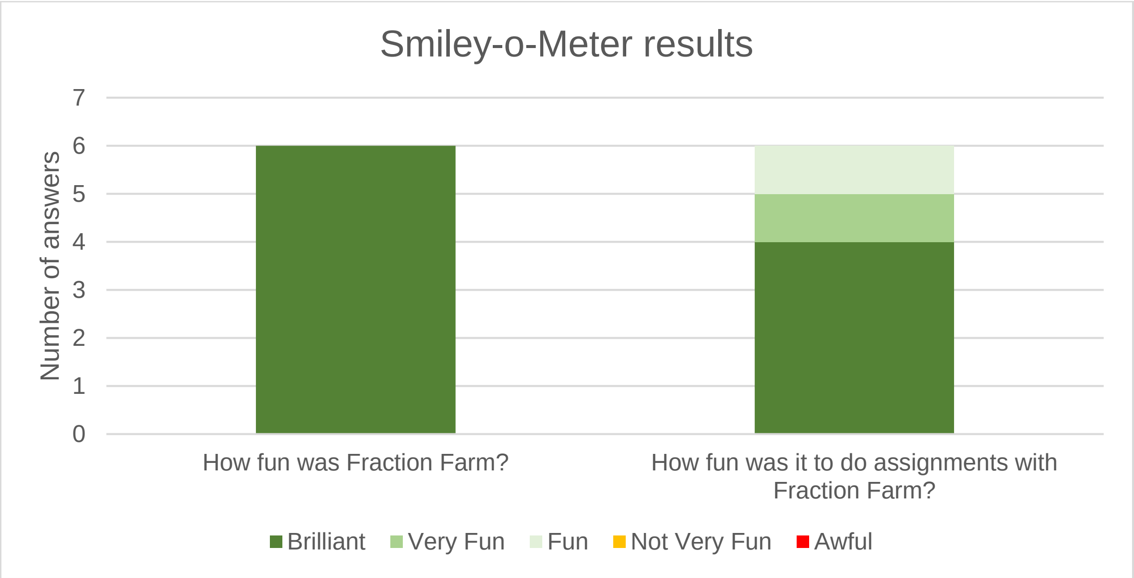


Figure 35. Results from the Smiley-o-Meter

For the card sorting, as seen in figure 36, there was a high level of variance between how the participants ranked all the design elements based on perceived fun. The assignments and animal icons were ranked the highest on average and the coins and lights were ranked the lowest on average. The feeding troughs were ranked with the least variance.

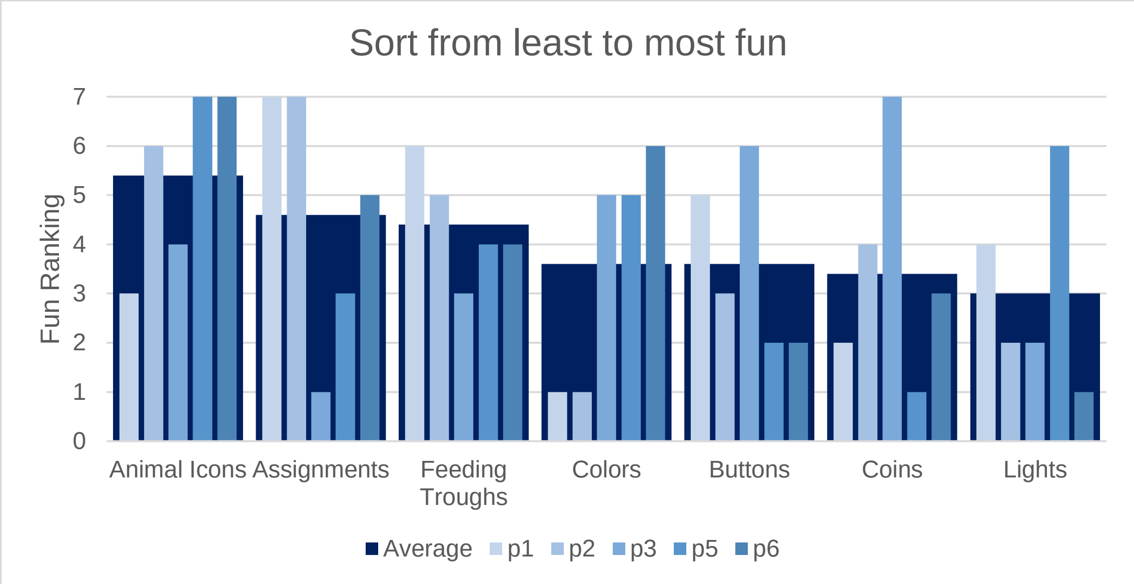


Figure 36. Results from the Card Sorting activity

ENDURABILITY

For the Again-Again table, all the children who filled in the table answered that they would like to play with Fraction Farm again (see figure 37). The interactive activities (feeding and pressing buttons) were rated highly as well, with the activities related to the assignments being rated slightly lower on returnance. Especially the activities related to the food coins were all rated lower.

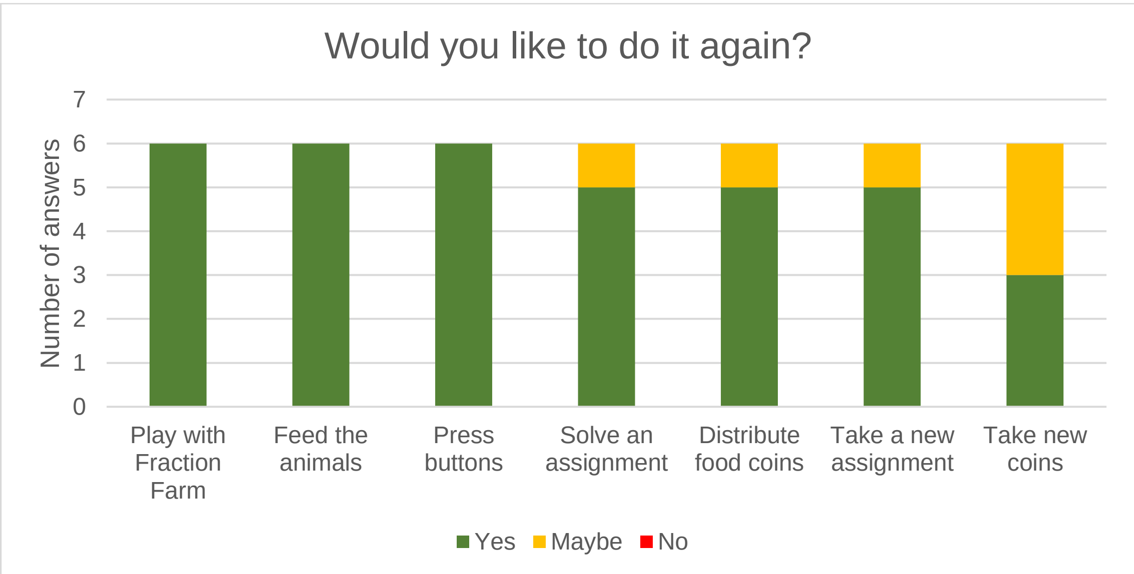


Figure 37. Results from the Again-Again table

5.3.2 QUALITATIVE RESULTS

We also collected qualitative data from the observations and “What did we do?” sheet. Originally the observation sheet was set up with the intention that it would allow for some quantification of the observations. By observing the number of times each action occurred each category of actions could be quantified somewhat. However, as the observations were done by 2 different observers for 2 different participants each, there was too much of a discrepancy between how the researchers counted to create a reliable quantification. Instead the observation sheet was mainly used to create notes regarding the types of behaviour. Behaviour regarding engagement and collaboration was still counted, but these counts were only used to state whether a significant number of behaviours signifying one of the variables was present. Embodied activity was measured by observing whether certain indicating behaviours occurred (so just *if* they occurred, not *how many times)*. See the Appendix for the filled in observation sheets. The 2 researchers discussed and cross referenced their findings after each session.

All the participants were also asked to rate the prototype from 1 to 10 at the end of each session. It was expected that all of them would rate very highly, and all the participants did indeed rate with a 10. This rating in and of itself does not mean anything, however if some participants would have given a poor rating, this would have been a strong indication that something would have been wrong with either the prototype or study design.

ENGAGEMENT

Overall participants showed many signs of engagement; lots of positive vocalizations, concentration signs and laughter were observed. A fair amount of disengagement signs were also observed, especially when solving the difficult 3rd assignment, or when other participants were being obtrusive. However, participants still wanted to stay and solve the assignment.

Participants who were done faster (worked quicker / had an easier task to solve) showed signs of boredom (participant 2: “because this is taking so long, I’m going to go to the toilet”). However, they also engaged with what the other participants were doing and tried to solve or help solve others’ tasks. For example, when participant 2 saw that her part was correct and that the others were still struggling, she started looking at what participant 1 was doing and tried to help.

Some participants also got disengaged when they realised that they had to do more complicated mathematical thinking. Participant 3 was observed saying “I don’t feel like doing maths”, when they were told that the more complicated assignment required some higher mathematical thinking than the first two.

COLLABORATION

A lot of interaction between participants was observed, both positive and negative. On the positive end, participants were observed thinking together, helping each other, handing things to each other, waiting on others, asking others for help and giving instructions. On the negative end they were grabbing coins without asking (“participant 4 stole everything from me!”), pressing other participant’s buttons, not waiting on the rest and ignoring others’ instructions. Especially in the second round (participants 5, 6, 7 and 8) the participants were more focussed on just solving their part rather than working together to solve the whole. The participants did try to get others to listen, but they often got in each other's way. Overall, objects were distributed a lot between participants, both positively and negatively.

We observed multiple participants temporarily taking on a kind of leadership role. Especially in the 1st round, participant 1 pushed the other participants to work together to solve the more difficult assignment. Participant 1 was able to reframe their understanding of fractions, and then managed to help the others so that the overall assignment could be solved correctly.

EMBODIED ACTIONS

Participants were seen doing a lot of exploring of the prototype. Participants did not wait for an explanation and started playing around with the prototype immediately. Grabbing coins and inserting them did not require any instruction for the children to start doing it, same with pressing the reset button. In round 2 participants wanted to try out what would happen if they put all the objects into one animals slot ("Can I put everything inside in one go?").

Furthermore, the participants pressed the check button a lot. Some participants were seen tapping the smiley icons. Participants were observed testing their ideas as fast as possible. Coins were just grabbed directly and then put in the slots, sometimes even from the food storage. The check button was often competed for by different participants ("No, I want to press the button!"), as they each individually wanted to know if what they did was correct.

Additionally, the participants explored the objects and their physical affordances. Objects were regularly divided by their type. In group 1 participants arranged all the necessary objects on the middle of the table, and then divided them over the different animals. These participants often shared objects between each other. In group 2 the participants got more in each other's way, preventing them from functionally sharing and arranging the objects between each other. As group 2 did not manage to solve assignment 3 by themselves, one of the observers gave them a visual explanation of what 1/3rd of 6 is, by taking 6 objects and dividing it into 3 groups of 2. After this, participant 7 applied this same method to solve the assignment.

Behaviour utilizing embodiment to explain concepts to others was also observed. Participant 8, who already had learnt some about fractions in school, tried to explain fractions to the observers and other participants by drawing a cake with her fingers on the table, dividing it in 4 pieces.

The participants also often identified themselves as the animals: "I am the chicken, so I need (…)", and personified them: "I (the chicken) can't get more apples, else I will get sick.", "The sheep needs (…)", "You're the chicken, so you don't need apples".

ENDURABILITY

Through the "What did we do?" sheets, some qualitative data regarding remembrance was also collected. Only 5 of the participants actually filled in the sheet, all of them choosing to draw the prototype. All 5 of these participants drew both the main table, including the animal icons, and the side table. Almost all of the participants drew the round table first, and then the animal icons, then the side table. Only 3 participants also drew the smileys, 3 drew the food troughs, and only 1 drew the coins. None of the participants drew the assignment cards.

CHAPTER 6. DISCUSSION & FUTURE WORK

The following parts describe the initial expectations for the results of the study prior to the conducting of the study, discussion of the results and study design, the implications of the results for the design of Fraction Farm and future work.

6.1 DISCUSSION

6.1.1 EXPECTED OUTCOMES

An important consideration for collecting data based on children's reported experience, is that they tend to rate their perceived fun quite highly as they want to please the researchers [15]. Additionally, the children at BSO De Vlinder are used to having user studies conducted there, and tend perceive these as fun and special activities. Based on this we expected the children to be primed to enjoy participating in the study, and to generally give very positive ratings and feedback. The utility of the collected data then also does not so much come from how highly the individual elements were rated enjoyability wise, but rather how they were rated compared to the other elements and how they were rated compared to our expectations.

EXPECTATIONS

When it came to the Smiley-o-Meter, the expectation was for participants to rate lower on the second question, as it pertained to the less playful and more to the academic, task-oriented side of the Fraction Farm (solving assignments). In general however, we expected that participants would rate their experiences quite highly, due to the reasons described in the previous paragraph.

ENDURABILITY

Similarly to the Smiley-o-Meter, with the Again-Again table it was expected that there would be a tendency for participants to want to repeat actions related to the assignments less, compared to the other activities. It was also expected that the participants would want to repeat the more interactive actions, such as pressing the buttons or feeding the animals. These elements were specifically designed to be enjoyable and engaging to use. We also expected for actions related specifically to the assignments to be rated lower in returnance.

Regarding the card sorting, we expected the colours, animal symbols, buttons and feeding troughs to be rated higher. Both the colours and animal symbols are design elements which stand out a lot, the colours being very bright and saturated, and the symbols being simple, clear and large. Because of this we expect the children to remember these elements more and thus rate them higher. For the buttons and feeding troughs we expect a similar outcome, once again due to their more interactive nature. Once again, we expected the assignments to be rated lower.

ENGAGEMENT & COLLABORATION

For engagement and collaboration it was expected that the participants would show a decent amount of engagement both with the prototype as well as with each other. Once again, the user study being perceived as a special activity could prime the participants into being more active and engaged than they normally might be. Children are also inherently social and all the participants would at least be somewhat familiar with each other at the after school care, making them fairly comfortable with interacting with each other.

EMBODIED ACTIVITY

As the participants of the user study ended up being a bit younger than the actual target user group of Fraction Farm, we assumed that they would probably have had less familiarity with fraction concepts than the target user group (9 to 10 year olds). Because of this we expected that the participants would probably not show too much understanding of division and fractions in how they would manipulate the food objects.

6.1.2 DISCUSSION OF RESULTS

EXPECTATIONS

Results from the Smiley-o-Meter were in line with what was expected according to children's tendency to rate perceived fun highly. As expected, some children rated the experience of solving assignments a bit lower than the overall experience. Participant 4, who rated this question the lowest seemed to also struggle a bit with concentrating on the assignments, especially with the most difficult one.

For the card sorting, there was a high level of variance between how the participants ranked all the design elements. This is somewhat to be expected with such a small sample size. Also important to note is that many of the participants said that they enjoyed all of the elements, seeming a bit reluctant to actually rank them. This could indicate that there was not really a big difference in how well the participants perceived the different elements. Nonetheless, some things can still be inferred from these results when looking at them relative to the other results and observations.

Looking at these results, they seem to go against the initial expectations somewhat. The assignments were rated quite highly on average and the colours and buttons ended up a bit lower on average than expected.

What stands out is that the assignments were ranked quite highly on average, albeit with very high variance. What might explain this is that participants 1 and 2 managed to solve their parts of the assignments with relative ease. When confronted with the more difficult 3rd assignment these participants (especially participant 1) were also more successful at reframing their understanding of the problem and then produce a correct answer. Participants 3 and 4, as well as all the participants in the second round all struggled with the 3rd assignment more and showed more signs of frustration when confronted with their inability to produce a correct answer.

Another point of interest is the low ranking of the lights and coins. For the lights, the low ranking could be explained by them being associated with getting negative feedback, as the LEDs are the main way in which the prototype tells the user they did something wrong. Participants seemed to also get frustrated when their efforts at correcting their incorrect answer did not lead to the green light turning on. As for the coins, their lower ranking falls in line with the results of the Again-Again table. Conflicts about the coins between participants and forgetting to put the right coins on the table at the start of an assignment could explain their low ranking here as well. This is further supported by the fact that less coin related conflicts were observed during round one. The participants from that round rated the coins higher on average than the participants in the second round.

For the colours and the buttons it is harder to analyse what might've caused their ranking. Participants in the first round rated the colours lower on average and rated the buttons higher. The ranking of the buttons could be tied to participants' capacity to solve the difficult assignment, similar to the assignments. Use of the buttons is tied to the users capacity to solve an assignment. If a user is struggling with solving a difficult assignment, they will most likely have to press the reset and check buttons more. This might create a more negative association with the buttons for users that struggle with the assignments more.

Finally, the ranking of the feeding troughs fell largely in line with our expectations. The variance in its ranking is also the lowest.

ENDURABILITY

For the Again-Again table, the results were in line with what was expected. All the children who filled in the table answered that they would like to play with Fraction Farm again. Once again this could in part be attributed to children's tendency to want to please the researchers and being primed to enjoy these kinds of activities. As expected, the interactive activities were rated highly as well. The slightly lower rating for the activities related to the assignments also once again matches the expectations.

What stands out are the activities related to the food coins. These results might be explained by the fact that we observed occasional conflicts arising between participants regarding the distribution of the coins between participants. This could have created a negative association with taking coins. Participants also did not always realise that they were supposed to have a specified amount of each food coin on the table for each assignment. Another likely explanation for the lower ranking of activities related to taking coins is that these were simply not very interactive. Distributing coins on the table and taking them from the storage did not provide the participants with any feedback from the system, whereas the other activities did.

Considering the outcomes of the "What did we do?" sheets it is interesting that only one participant described the food coins. A possible explanation for this is that the food coins very naturally served as an extension of the users, the use of the food coins being so intuitive that they were not remembered as a part of the system, but more as a part of the users own cognitive operation.

ENGAGEMENT

Participants seemed very engaged. Again, important to keep in mind is that taking part in these studies is seen as a fun and special activity by the children at the BSO, so the participants were already primed before they see the prototype.

The disengagement caused by an inability to solve the difficult assignment seemed to be tied to a lack of knowledge about fraction concepts. The 1st and 2nd assignments could be solved by merely looking at the numerator and inserting that amount. It was apparent that participants were using this method, because this method does not work for the 3rd assignment, where the denominator did not always match the number of an object. Yet all participants still initially tried to apply this method for the 3rd assignment as well. When confronted with the fact that this method was not working, participants showed signs of frustrations and even blamed the prototype itself. Participant 6's first reaction was to say that "It's broken!", and other participants also made similar remarks ("What did I do wrong?"). While disengagement was observed at times, nobody wanted to quit, suggesting that they were still motivated to work with the prototype, despite getting frustrated.

COLLABORATION

The amount of observed interaction between the participants was higher than expected. Initially we had not considered the extent to which users could also get in each other's ways. Especially as the participants seemed very engaged, being very keen on exploring their own ideas. This probably led to the participants not taking into account how they might obstruct their fellow participants.

Considering the distinction between cooperation and collaboration provided in [9], a decent amount of both cooperative and collaborative behaviour was observed. When all the participants were confident in their capacity to solve their respective parts of the assignments, they acted more cooperatively, sticking to their own understanding of the task. The moment the assignments got more difficult, the participants got more involved with each other's understanding of the problem and tried to create a more collective understanding to tackle the challenge. While the collaborative efforts did also lead to conflict, as not every participant had the same capacity to understand the problem, they did help the participants of group 1 to solve the 3rd assignment.

EMBODIED ACTIONS

Use of the system seemed very intuitive and enable embodied actions, as children did not require explanation to start interacting with the Fraction Farm prototype and exploring its affordances. Actions related to the exploration of the prototype's affordances can be categorized as empiric actions as opposed to pragmatic ones, as they are actions aimed at creating an internal structure and understanding of the prototype's function. However, it is not always clear when an action, such as pressing a button, serves as exploration of affordances and function, as opposed to simply being pragmatic action necessary for using the system.

The participants tended to just test their ideas as fast as possible, as opposed to first laying their answer out physically on the table. Because of this, it seemed that the participants wanted quick feedback on what they were doing; rapid trial and error. Some participants were observed tapping the smiley icons, which could be explained by a desire for more feedback or an impression that that the system was not working properly. The exploration of the objects and their affordances also aligns with the participants trial and error approach.

While some actions that seemed to act as scaffolding for fraction operations were also observed, the results seem to largely fall in line with what was expected. Only the participants that had some experience with fraction concepts were clearly seen creating some kinds of physical representations and distributions related to fractions.

Finally, the observation of embodied actions reliably is quite difficult. As mentioned at the start of this section, clearly distinguishing epistemic actions is hard. Spotting a specific kind of behaviour gets even more difficult when there is a lot going on an many actions are taking place simultaneously. However based on what was observed we can say with some confidence that the Fraction Farm system does enable embodied engagement. The degree to which it enables embodied engagement and how it affects their learning performance of fraction concepts would have to be studied in future research however.

6.1.3 FINDINGS RELATED TO THE GUIDELINES

Finally, we consider the study results regarding the implementation of the Tangible Learning Design Framework [9] in the Fraction Farm prototype.

INFO PROCESSING

1. Distributing information across modalities can increase effective working memory capacity

Implementation: Feedback through lights; Information communicated through visible and tactile (engraved) icons; Freely manipulatable / distributable objects allow for information distribution; zones separated by colour, connection to the assignments is communicated with the same colours

Observations: Feedback through lights seemed to be clear, participants understood what the different colours communicated. Icons were clear and intuitive to the participants (connection between the icons on the assignments and on the coins / table, participants were able to distinguish between the different icons). Participants had no issues connecting the symbols and colours and icons on the assignments to the colours and icons on the table.

2. Making mappings between the form and behaviour of physical and/or digital objects and real-world entities coherent can reduce extraneous cognitive load

Implementation: The objects represent foods; The various zones for the food objects represent animals that would consume said foods

Observations: The connection to food was very clear. Participants often argued from the perspective of the animal that they were 'feeding' ("I need", "this animal needs"). Whether this lead to reduced extraneous cognitive load is not evident however.

CONSTRUCTIVIST

3. Creating authentic tasks and using personal objects can support learners in forming individually meaningful goals for interacting with the TUI

Implementation: Framing the assignments as resource management of food for animals; making the animals happy when the assignment is completed correctly

Observations: Identification with the animals and arguing from their perspective could be an indication of the participants forming individually meaningful goals.

4. Using spatial, physical, temporal or relational properties can slow down interaction and trigger reflection

Implementation: The food slots only allow for one food object to be inserted at a time; Users have to manually take a new assignment card out of the assignment storage and place it into the assignment zone to start a new assignment

Observations: Interaction slowed down whenever a new assignment had to be started. Sometimes participants were too quick to start with a new assignment, forgetting to properly take the right amount of coins at the start. The food slots also seemed to slow down the interaction: participants were seen recounting what they decided belong in each slot as they were inserting the coins.

EMBODIED

5. Distributing parts of mental operations to actions on physical and/or digital objects can simplify and support mental skills

Implementation: Information communicated through visible and tactile (engraved) icons; Freely manipulatable / distributable objects allow users to create tangible and visual representations of the fractions they have to create

Observations: Only a few participants were seen creating distributions of the coins that could support their understanding of fractions. Distribution of the coins between participants or the animals was used as a strategy to better understand the assignment.

6. Leveraging image schemas in input actions can improve usability and system learnability

Implementation: Inserting objects counts them, removing them removes them from the count (in- out image schema)

Observations: The mechanics of the food troughs did seem intuitive. Participants understood immediately that they were supposed to put the coins inside the slots. It also seemed clear to them that ejecting the coins from the troughs using the buttons meant that those coins were no longer counted for the answer.

7. Using conceptual metaphor(s) based on image schemas to structure interaction mappings may bootstrap learning of abstract concepts

Implementation: The food objects of a specific type are all clearly connected in such a way that the objects together create either one clear set or one complete object (part of a whole / set image schema). This bridges to the abstract concept of fractions, as the mathematical description "1/4" can be physically represented as one object belonging to a set of four or one part of a whole object split in four pieces.

Observations: For the participants who had already some knowledge concerning fractions, the image schema of a pie divided into equal pieces was most commonly referred to. This image schema was not present in the design. Participants did not seem to utilize the part of a whole / set image schema much or correctly, as they tended to try to solve the assignments by only looking at the numerators of the fractions. This is probably due to a lack of familiarity with any formal fraction concepts.

DISTRIBUTED

8. Designing objects that allow spatial reconfiguration can enable mutual adaptation of ideas

Implementation: Freely manipulatable / distributable objects allow for spatial reconfiguration

Observations: Participants did not utilize spatial reconfiguration much. They tended more to just directly insert objects into the food slots and then seeing if the answer was correct, instead of creating spatial configurations of their answers first. When participants did configure the object spatially, it tended to help them get a better understanding of what they were doing wrong, and what the assignment was asking of them.

9. Using concrete representations can support interpretation of symbolic representations of abstract concepts

Implementation: The food objects of a specific type are all clearly connected, both physically (same shape), visually (same icon) and as a metaphor (grain, fruit or water for the animals to consume). This way the mathematical description "1/4 of the grain" written on the assignment card is physically represented as one grain object belonging to a set of four, as well as a metaphor as one fourth of the available grain.

Observations: The concrete representations (feeding animals) seemed to be quite intuitive to the participants. Some participants even identified as the animals and, thinking from the perspective of what they would 'need' “I am the chicken, so I need (…)”, and personified them: “I (the chicken) can’t get more apples, else I will get sick.”, “The sheep needs (…)”, “You’re the chicken, so you don’t need apples”. However, the connection to fractions did not seem to be made often, most likely due to a lack of prior knowledge with fractions. As this study did not measure participants' knowledge gain regarding fractions, it is hard to say whether the concrete representations served as a support for understanding the symbolic representations of fractions.

COLLABORATIVE

10. Creating configurations in which participants can monitor each other’s activity and gaze can support the development of shared understandings

Implementation: The table is deliberately round and flat, making it easy for participants to monitor each other's activity at the table

Observations: Participants often glanced at each other's actions and objects. Development of shared understandings was observed to some extent. For example, participant 1 tried to show the other participants how they thought the 3rd assignment needed to be solved.

11. Distributing roles, information and controls across the TUI learning environment can promote negotiation and collaboration

Implementation: The layout of the table suggests distributing users over the 4 different zones

Observations: Participants focussed mainly on their own animal / zone. Collaboration did occur, with participants dividing coins between each other and helping each other. However, the participants also got in each other's way (grabbing coins without asking, pressing buttons without asking).

12. Creating constrained or co-dependent access points schemes can compel learners to negotiate with each other

Implementation: The object insertion slots for the different zones are fairly far away from each other, promoting interaction with multiple users

Observations: As only one check button was present, there was competition and conflict over who could press the check button. Participants did not very often insert coins into the slots of other animals than the one they were assigned to, usually waiting on all participants to complete their part of the assignment.

6.1.3 STUDY DESIGN LIMITATIONS

After conducting the study, some limitations of the study design became evident.

Firstly, the sessions seemed to last a bit too long for the attention span of the children. After interacting with the prototype for 30 minutes, it was difficult to get the participants to spend another 15 minutes answering the interview questions in a somewhat concentrated manner. Because of this we were even unable to get all of the participants to actually complete the interview questions.

Furthermore, there were too many different variables to consider during the observations. The observation sheets should have probably been limited to only 1 or 2 variables and 1 page, instead of 3 variables covering 2 whole pages. The large amount of things to pay attention to made it difficult to properly observe the actions of the participants.

Finally, audio recordings of the sessions would have proven very beneficial for creating proper transcripts of the sessions. The only records of the user study that were made now were short notes and written a description of the events based on what could be recollected.

6.2 FUTURE WORK

6.2.1 DESIGN IMPLICATIONS FOR FUTURE DEVELOPMENT

Based on the results and observations from the study we can establish some key take aways for potential future development of the Fraction Farm system. We also evaluate how well the Tangible Learning Design Framework was implemented.

ENJOYABILITY & ENGAGEMENT

The results indicate that the Fraction Farm prototype was fun and engaging to use. While disengagement and frustration was also observed, this is not necessarily a bad thing. Some degree of frustration is expected when confronted with a difficult task, especially one that requires the reframing of prior knowledge. However, Fraction Farm can be improved upon to allow struggling students to still enjoy using it.

The difficulty of the assignments should be considered further, together with a more defined context for Fraction Farm’s use in the classroom. Assignments introducing different fraction concepts should coincide with when the teacher introduces these concepts to the class. As Fraction Farm is not intended to be a system which could teach fractions to children all by itself, further consideration should be put into in which phase(s) of the learning process it should be implemented. The role of the teacher and how much they should be involved with helping students use Fraction Farm is also a point of consideration.

COLLABORATION

The degree to which users could get in each other’s way was not much considered in the design of the Fraction Farm prototype. The presence of only one button that could be pressed to get feedback on the users answers seemed to be a problem. With the prototype, users had to compete over the button to get feedback, other users at times getting feedback when they did not want it. Future design should take this in consideration. Check buttons for each animal zone could be implemented. This would allow users to check individually for each zone whether or not the animal has the correct amount of each food type, without interfering with the others.

However, if the goal of the design is to promote collaboration over just cooperation, more consideration could be put into how multiple users should use fraction farm together. The 4 sections of the table seemed to promote more of a cooperative and split up way of working, where users largely focussed on their own section. A possible implementation that could promote more collaboration are assignments which require sets of animals to have a certain fraction of the food (for example, the cow and pig together should have 2/3rds of the grain). This way, the children working on the cow and pig would have to collaborate to solve that part of the assignment.

EMBODIED DESIGN

It is difficult to say to what extent the participants really engaged in an embodied manner with fraction concepts during the user study. A lack of clear physical fraction representation strategies being observed could have multiple explanations. Firstly, perhaps creating these representations is not that effective of a strategy after all (considering [8] and the evidence it shows for the advantages and use of physical distribution for understanding fractions this seems unlikely). Secondly, as mentioned before, the participants' younger ages and lack of familiarity with formal fraction concepts could have prevented them from fully utilizing the manipulatives. Third, it is possible that the design of Fraction Farm did not enable the application of these kinds of strategies sufficiently. Finally, it could also be that the participants did apply these strategies a decent amount, and that the observers were simply not able to identify these strategies successfully in the moment.

Most likely all of these explanations have some degree of truth to them. Future development should therefor consider all these points and how (if) the design should further enable embodied engagement with fraction concepts.

One design feature that ended up not being present in the prototype of Fraction Farm is the use of fraction represented as parts of a sort of pie. This representation is commonly used in primary school when first introducing fractions and is something that children introduced to fractions will most likely be familiar with. Some kind of feature that would allow users to create tangible representations of this pie fraction image schema to help them solve the assignments could be a great addition to Fraction Farm.

Another feature that ended up not being implemented into the prototype was the use of audio. As mentioned in the design chapter and the Tangible Learning Design Framework [9], multimodal feedback can be a great way to reduce cognitive load and make feedback more intuitive. Implementing audio feedback in the form of animal sounds could also make the system even more engaging and fun to interact with, as well as strengthen the narrative and immersion. Future development should definitely consider some way of utilizing audio into the design.

TANGIBLE LEARNING DESIGN FRAMEWORK

Looking at the results of the user study related to the Tangible Learning Design Framework, it seems that the framework was implemented fairly successfully. Some of the guidelines could be explored further for future work, especially related to the before mentioned considerations for future work. Reference to and use of the framework definitely proved fruitful in creating a design that was well grounded in the underlying theories and effectively applied them. Future work should therefor keep grounding itself in this framework (and other frameworks of similar quality).

6.2.2 FUTURE RESEARCH

The study conducted for this project did not provide any quantitative evidence regarding the effectiveness of Fraction Farm at improving the learning of fraction concepts. To get a good idea of the potential learning benefits of a system like Fraction Farm in teaching fractions, a study focussed on measuring learning gain would have to be conducted.

Furthermore, studying how to properly identify and quantify embodied and tangible engagement also warrants further research. The ability to reliably measure to what extent users of a tangible learning system actually engage in an embodied manner could be a great tool for designers and researchers creating and testing these systems. To be able to justify the benefits of a tangible learning system on its ability to engage users in an embodied manner, we should be able to prove that users are in fact actually engaging in an embodied manner.

CHAPTER 7. CONCLUSION

After the design, construction and evaluation of the Fraction Farm prototype it is evident that the design of TLE's is a complex process, requiring consideration of many design elements as well as the intended learning goals of the TLE. Due to the complexity of the design space, design choices should be grounded in the underlying theories and related work and design frameworks. Additionally, testing the design of a system like this in the wild is crucial to creating a learning tool that has real positive impact.

With regards to the developed Fraction Farm prototype we can say that the design goals were achieved. Using the prototype was observed to be fun, engaging and enabled interaction and collaboration between users. The prototype allowed users to engage in a tangible manner, and helped users solve a fairly challenging fraction problem. The degree to which using Fraction Farm truly leads to a tangible learning experience and improved understanding of fraction concepts is not evident from research so far however.

The findings of the evaluation indicate that the prototype operates well enough to warrant future research. Furthermore, it points to the use of a tangible learning tool for teaching fraction concepts to be warranted. In its current state, Fraction Farm seems to be fun and engaging for children to use. There seem to be some indications that it could work well as a learning tool, however future study is required to conclusively say anything concerning its role in a classroom. Especially as this evaluation did not quantitively measure tangibility or the impact on the participants understanding of the learning material, future research is required to truly gain insights into the efficacy of Fraction Farm.

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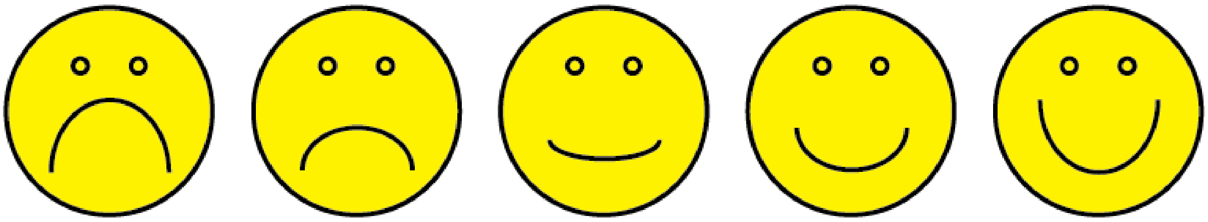
APPENDIX

A: INTERVIEW QUESTIONS

Participant No: __________

Hoe leuk vond je Breuken Boer?

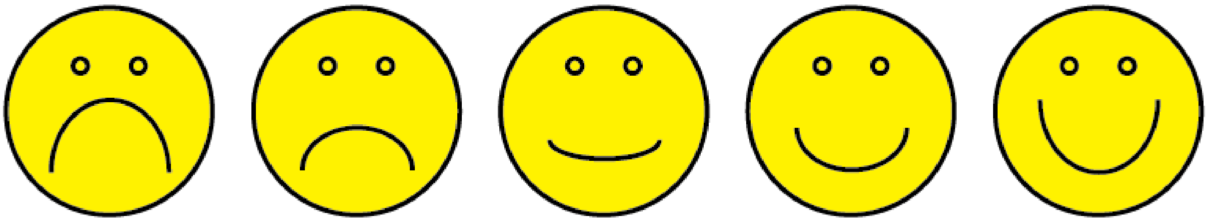
Omcirkel jouw antwoord



Stom | Niet heel leuk | Leuk | Heel leuk | Geweldig

Hoe leuk vond je het om opdrachten met Breuken Boer te doen?

Omcirkel jouw antwoord



Stom | Niet heel leuk | Leuk | Heel leuk | Geweldig

Participant No: _________

Zou je het nog een keer willen doen?

Vink jouw antwoord aan

	Ja	**Misschien**	**Nee**
Met Breuken Boer spelen			
Een opdracht oplossen			
Voedsel munten verdelen			
De dieren voeren			
Knoppen indrukken			
Nieuwe munten pakken			
Een nieuwe opdracht pakken			

Participant No: _________

Wat hebben we gedaan?

(schrijf / teken / vertel)

Participant No: _________

Hoe zou jij Breuken Boer beter maken?

(Schrijf / Teken / Vertel)

Study Observation Sheet

Observer: __________

Participant No: __________

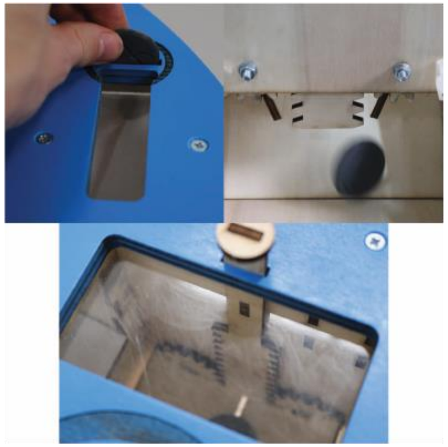
Behaviour	No of times	Special notes
Signs of engagement		
Smiles / laughing		
Concentration signs (fingers in mouth, tongue out)		
Excitable bouncing		
Positive vocalization		
Signs of disengagement		
Frowns		
Signs of boredom (ear playing, fiddling)		
Shrugs		
Negative vocalization		
Signs of collaboration		
Asking others for help / talking to others		
Peeking at others' work		
Helping others		
Joining efforts on one task		

Behaviour	No of times	Special notes
Intrinsic actions with feedback		
Pressing the check button		
Pressing the reset buttons		
Placing a (new) assignment card in the active zone		
Inserting food objects into an animals food trough		
Intrinsic actions without feedback		
Moving objects from the food storage to the table		
Moving objects from the food trough back to the table after pressing the reset button		
Signs of embodied interaction		
Arranging objects by type		
Arranging objects by the animal they belong to (before insertion)		
Dividing objects between participants		
Arranging physical representations of fractions using the objects		
Exploration signs; Grabbing, looking, rotating, comparing, etc.		
Emergent behaviours		

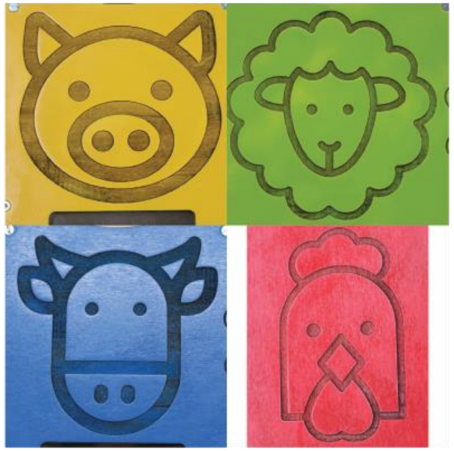
C: CARD SORTING CARDS

Opdrachten

Munten



Voederbakken

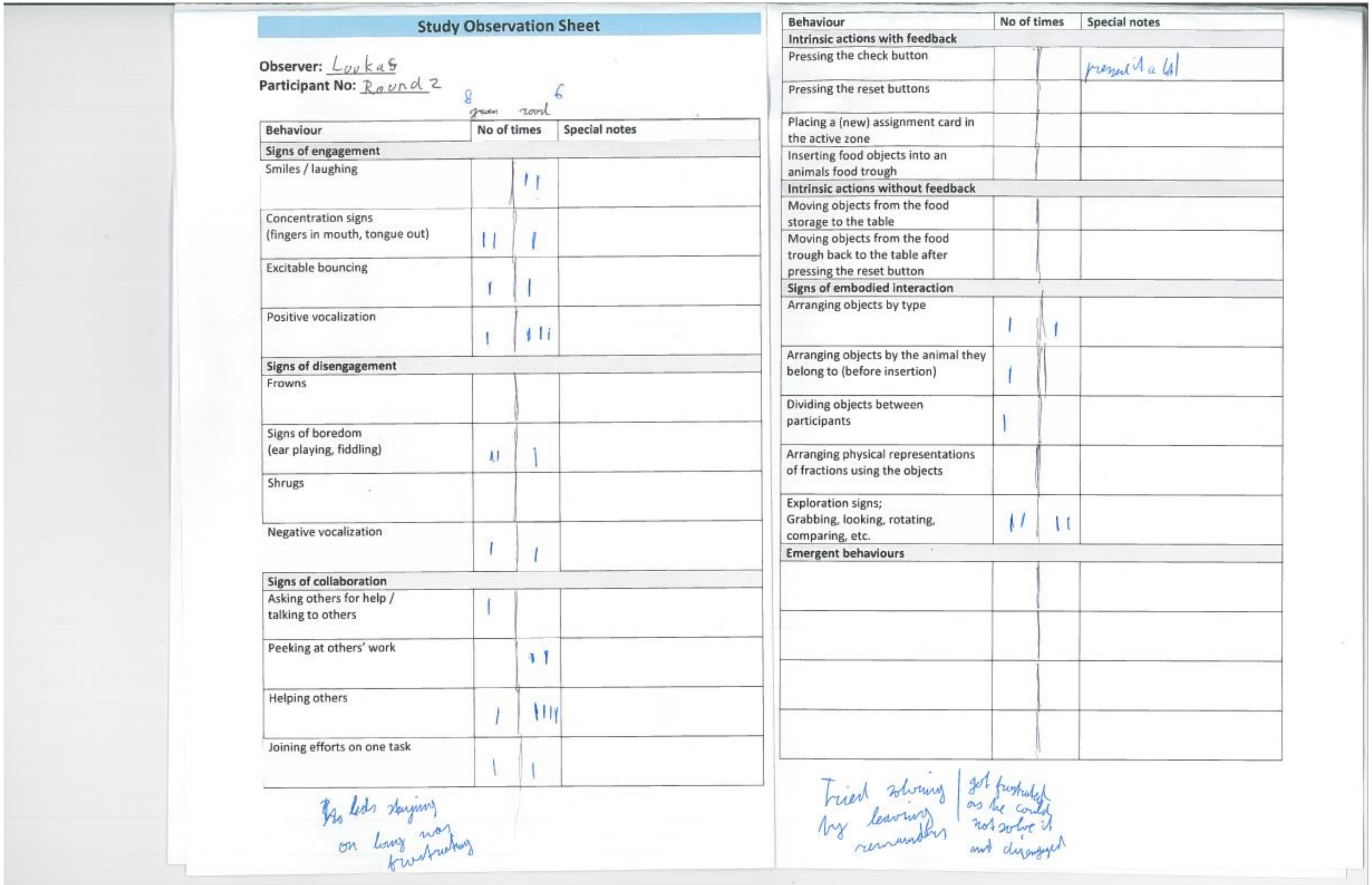


Dier Symbolen

Kleuren

Lampjes

Knoppen



Study Observation Sheet

Observer: Loukas
Participant No: Round 2

Behaviour	No of times (8 green)	No of times (6 rood)	Special notes
Signs of engagement			
Smiles / laughing		II	
Concentration signs (fingers in mouth, tongue out)	II	I	
Excitable bouncing	I	I	
Positive vocalization	I	III	
Signs of disengagement			
Frowns			
Signs of boredom (ear playing, fiddling)	II	I	
Shrugs			
Negative vocalization	I	I	
Signs of collaboration			
Asking others for help / talking to others	I		
Peeking at others' work		II	
Helping others	I	IIII	
Joining efforts on one task	I	I	

Both kids staying on long was frustrating

Behaviour	No of times		Special notes
Intrinsic actions with feedback			
Pressing the check button			pressed it a lot
Pressing the reset buttons			
Placing a (new) assignment card in the active zone			
Inserting food objects into an animals food trough			
Intrinsic actions without feedback			
Moving objects from the food storage to the table			
Moving objects from the food trough back to the table after pressing the reset button			
Signs of embodied interaction			
Arranging objects by type	I	I	
Arranging objects by the animal they belong to (before insertion)	I		
Dividing objects between participants	I		
Arranging physical representations of fractions using the objects			
Exploration signs; Grabbing, looking, rotating, comparing, etc.	III	II	
Emergent behaviours			

Tried solving by leaving reminders | got frustrated as he could not solve it and disengaged

2 Cirkel

Study Observation Sheet

Observer: ________ hiet echt met elkaar.

Participant No: ________

Behaviour	No of times	Special notes
Signs of engagement		Kadlaupie:
Smiles / laughing b	II	he e-staat niet leuk
g	I	helpt a…
Concentration signs (fingers in mouth, tongue out) b		
g	II	tong in de mond, hand op de kin
Excitable bouncing b	I	yaa!!
g	I	Yay! bij goed mais
Positive vocalization b	II	'dit is echt een leuk spel' zei hij tegen…
g		
Signs of disengagement		
Frowns b		
handen over elkaar g	II	→ sip gezicht
Signs of boredom (ear playing, fiddling) b		
g		
Shrugs b	I	wat hoe krijg je het, [illegible] elkaar
g		
Negative vocalization b	I	he dit ding is kapot.
geel nee g	I	wat heb ik verkeerd gedaan?
Signs of collaboration		
Asking others for help / talking to others b	II	grasses? wat doe je? jij hebt kip dan; je hebt nog niet…
kan je antwoord zeggen? g	I	druk V, druk V… → gevraagd.
Peeking at others' work b	I	
g		
Helping others b	I	iedereen samen
g	II	ja… ik sorteer-doet ook…
Joining efforts on one task b	I	ik heb appels nodig, bij ana
g		

goede blauw ← blokken elkaar met ordinest – "groen hee ik wil drukken!"

Dit pakt al dingen voordat het verteld wordt.

Meisje rood, 6 7 · meisje geel, groen, 7 · jongen blauw 8 · meisje niet 7, laatste groen · maar eigenlijk niet

Behaviour	No of times	Special notes
Intrinsic actions with feedback		
Pressing the check button		vaak
Pressing the reset buttons		Regelmatig.
Placing a (new) assignment card in the active zone		moeizaam, te snel.
Inserting food objects into an animals food trough		ok
Intrinsic actions without feedback		
Moving objects from the food storage to the table		met hulp.
Moving objects from the food trough back to the table after pressing the reset button		alleen einde
Signs of embodied interaction		
Arranging objects by type		v
Arranging objects by the animal they belong to (before insertion) X		deze groot, leggen dat niet.
Dividing objects between participants X		
Arranging physical representations of fractions using the objects X		alleen met uitleg
Exploration signs; Grabbing, looking, rotating, comparing, etc.		wel veel uitgeprobeerd
Emergent behaviours		

groen bij uitleg, zo moet het, en nu weet ik het zeker… vergeten ordracht te leggen.

instructie gegeven bij ordracht 1 alleen geel goed. | groen kapot, want ik zou nog niet kiezen

je groen: mag ik een keer alles erin doen → kijken wat er gebeurt…

28:24 to solve everything

Study Observation Sheet

started solving greens problem

Observer: Lookas

Participant No: Round 1 8 8

green wool

Behaviour	No of times		Special notes
Signs of engagement			
Smiles / laughing	I II I	III	
Concentration signs (fingers in mouth, tongue out)	III	I	
Excitable bouncing	·		
Positive vocalization	I		
Signs of disengagement			
Frowns	I		
Signs of boredom (ear playing, fiddling) yawn	I	III	
Shrugs		·	
Negative vocalization	I		
Signs of collaboration			
Asking others for help / talking to others	II	I	
Peeking at others' work	III	IIII	
Helping others	IIII IIII	IIIII	leiden initiatief
Joining efforts on one task	III	III	

led afterwards

was more quiet

was faster (easier task) got bored

Behaviour	No of times		Special notes
Intrinsic actions with feedback			
Pressing the check button			no veel
Pressing the reset buttons			veel
Placing a (new) assignment card in the active zone			✓
Inserting food objects into an animals food trough			✓, soms
Intrinsic actions without feedback			
Moving objects from the food storage to the table			moest even herinnerd worden
Moving objects from the food trough back to the table after pressing the reset button			II
Signs of embodied interaction			
Arranging objects by type	II		
Arranging objects by the animal they belong to (before insertion)	I	I	
Dividing objects between participants	I	I	
Arranging physical representations of fractions using the objects			
Exploration signs; Grabbing, looking, rotating, comparing, etc.	✓	✓	
Emergent behaviours			

started organizing what the sheep needed blauw & geel Rood: 1 d. moeilijk [illegible]

Study Observation Sheet

Observer: ________ tout, fout, kijk na

Participant No: ________

Behaviour		No of times	Special notes
Signs of engagement			
Smiles / laughing	b	I	ja
	g		
Concentration signs (fingers in mouth, tongue out)	b		
	g	I	looks at light
Excitable bouncing	b	I	doet vinger
	g		
Positive vocalization geel raakt leeuw	b	II	goed, kleur, [illegible]
	g	I	nee hoor, goed!
Signs of disengagement			
Frowns niet kunnen zien	b		
	g		
Signs of boredom (ear playing, fiddling)	b	II	verkeerde, [illegible] koe, [illegible]
Yawning	g		
Shrugs niet gezien	b		
	g		
Negative vocalization	b	I	in tekst
	g		
Signs of collaboration			
Asking others for help / talking to others	b	II	Koeis [illegible], ik heb 2 [illegible]
	g	I	laten we .. de
Peeking at others' work	b		ja meer lost..
	g		
Helping others	b		
	g	I	instructies
Joining efforts on one task	b		
b: zullen we wisselen	g	I	[illegible]

b: - Jasper heeft alles van mij gestolen
- houdt geel tegen

dugs eerste met [illegible] B: ik heb gaan tijn [illegible]

2 wel
3 [illegible] niet, hebben ze volgens mij [illegible]

- gaat iets 'tallened uit [illegible]
- legt hem in het midden
één blijft staan

Behaviour	No of times	Special notes
Intrinsic actions with feedback		
Pressing the check button	vaak	
Pressing the reset buttons	vak	
Placing a (new) assignment card in the active zone	[illegible]	
Inserting food objects into an animals food trough	gaat [illegible]	controleren [illegible]
Intrinsic actions without feedback		
Moving objects from the food storage to the table		na [illegible]
Moving objects from the food trough back to the table after pressing the reset button		als het goed is
Signs of embodied interaction		
Arranging objects by type	1	
Arranging objects by the animal they belong to (before insertion)	1	[illegible]
Dividing objects between participants		
Arranging physical representations of fractions using the objects	X	niet ontdekt !
Exploration signs; Grabbing, looking, rotating, comparing, etc.		ja [illegible]
Emergent behaviours		
goed, kunnen we 1 wear doen		

moeten allen doe die [illegible]

Rood iemand geen [illegible]

blauw: ik heb ...

Rood omdat dit zo lang duurt ik ga hem [illegible]

- instructie gegeven : misschien is deze wel moeilijk

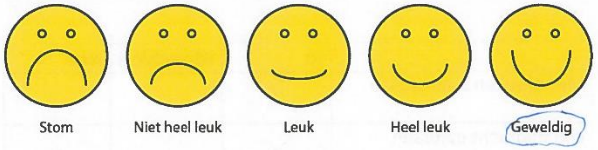
E: INTERVIEW RESULTS

Round 1 groen

Participant No: 1

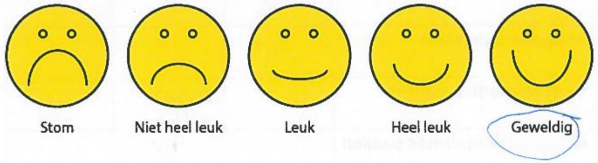
Hoe leuk vond je Breuken Boer?

Omcirkel jouw antwoord



Hoe leuk vond je het om opdrachten met Breuken Boer te doen?

Omcirkel jouw antwoord



Participant No: ______

Zou je het nog een keer willen doen?

Vink jouw antwoord aan

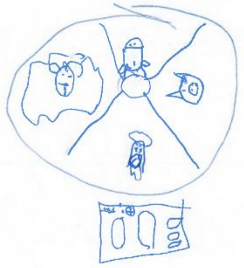
	Ja	Misschien	Nee
Met Breuken Boer spelen	X		
Een opdracht oplossen	X		
Voedsel munten verdelen	X		
De dieren voeren	X		
Knoppen indrukken	X		
Nieuwe munten pakken		X	
Een nieuwe opdracht pakken		X	

Round 1 groen

Participant No: 1

Wat hebben we gedaan?

(schrijf / teken / vertel)



Participant No: 10

Hoe zou jij Breuken Boer beter maken?

(Schrijf / Teken / Vertel)

Meer dieren

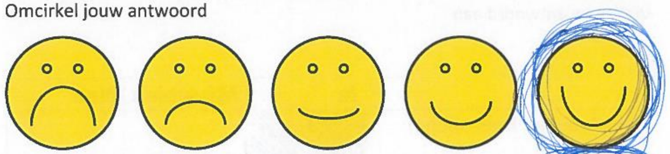
echt eten oh nee toch niet.

Round 1 rood

Participant No: 2

Hoe leuk vond je Breuken Boer?

Omcirkel jouw antwoord



Stom | Niet heel leuk | Leuk | Heel leuk | Geweldig

Hoe leuk vond je het om opdrachten met Breuken Boer te doen?

Omcirkel jouw antwoord

Stom | Niet heel leuk | Leuk | Heel leuk | Geweldig

Participant No: ________

Zou je het nog een keer willen doen?

Vink jouw antwoord aan

	Ja	Misschien	Nee
Met Breuken Boer spelen			
Een opdracht oplossen			
Voedsel munten verdelen			
De dieren voeren			
Knoppen indrukken			
Nieuwe munten pakken			
Een nieuwe opdracht pakken			

Participant No: ________

Hoe zou jij Breuken Boer beter maken?

(Schrijf / Teken / Vertel)

Meer dieren

Round 1 rood

Participant No: 2

Wat hebben we gedaan?

(schrijf / teken / vertel)

dit hebben we gedaan

Round 1 blauw

Participant No: 3

Hoe leuk vond je Breuken Boer?

Omcirkel jouw antwoord

Stom | Niet heel leuk | Leuk | Heel leuk | Geweldig

Hoe leuk vond je het om opdrachten met Breuken Boer te doen?

Omcirkel jouw antwoord

Stom | Niet heel leuk | Leuk | Heel leuk | Geweldig

Participant No: ________

Zou je het nog een keer willen doen?

Vink jouw antwoord aan

	Ja	Misschien	Nee
Met Breuken Boer spelen	X		
Een opdracht oplossen	X		
Voedsel munten verdelen	X		
De dieren voeren	X		
Knoppen indrukken	X		
Nieuwe munten pakken	X		
Een nieuwe opdracht pakken	X		

Participant No: 10000

Hoe zou jij Breuken Boer beter maken?

(Schrijf / Teken / Vertel)

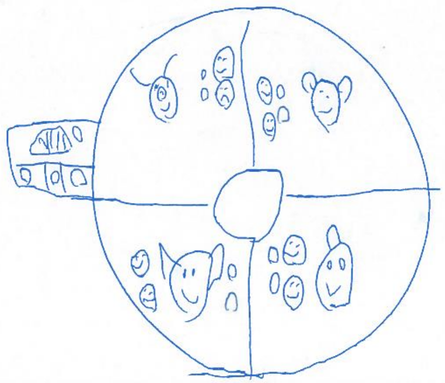
Meer eten!!!

Roond 1 blauw

Participant No: 3

Wat hebben we gedaan?

(schrijf / teken / vertel)



Round 1 geel

Participant No: 4

Hoe leuk vond je Breuken Boer?

Omcirkel jouw antwoord

Stom | Niet heel leuk | Leuk | Heel leuk | Geweldig

Hoe leuk vond je het om opdrachten met Breuken Boer te doen?

Omcirkel jouw antwoord

Stom | Niet heel leuk | Leuk | Heel leuk | Geweldig

Participant No: ________

Zou je het nog een keer willen doen?

Vink jouw antwoord aan

	Ja	Misschien	Nee
Met Breuken Boer spelen	X		
Een opdracht oplossen	X		
Voedsel munten verdelen	X		
De dieren voeren	X		
Knoppen indrukken	X		
Nieuwe munten pakken	X		
Een nieuwe opdracht pakken	X		

Participant No: ________

Hoe zou jij Breuken Boer beter maken?

(Schrijf / Teken / Vertel)

om
eten

Round 1 geel

Participant No: 9

Wat hebben we gedaan?

(schrijf / teken / vertel)

bla
bla
bla
bla
bla

Round 2 rood

Participant No: 5

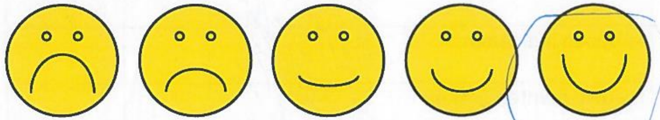
Hoe leuk vond je Breuken Boer?

Omcirkel jouw antwoord

Stom | Niet heel leuk | Leuk | Heel leuk | Geweldig

Hoe leuk vond je het om opdrachten met Breuken Boer te doen?

Omcirkel jouw antwoord



Stom | Niet heel leuk | Leuk | Heel leuk | Geweldig

Participant No:

Zou je het nog een keer willen doen?

Vink jouw antwoord aan

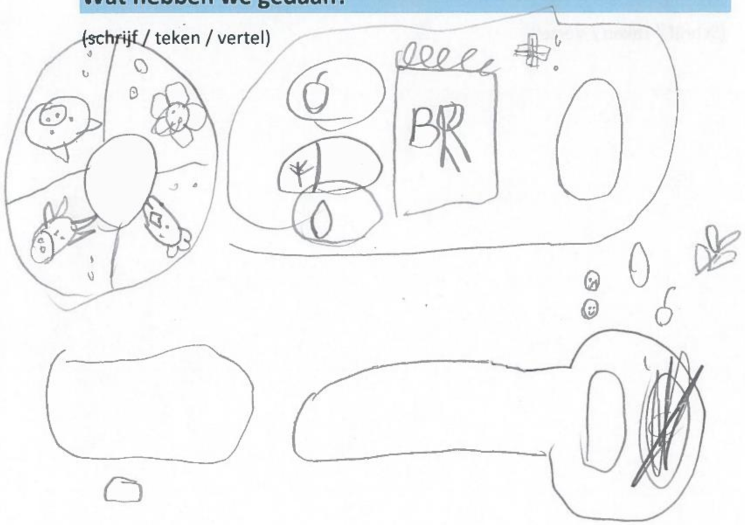
	Ja	Misschien	Nee
Met Breuken Boer spelen			
Een opdracht oplossen			
Voedsel munten verdelen			
De dieren voeren			
Knoppen indrukken			
Nieuwe munten pakken			
Een nieuwe opdracht pakken			

Round 2 rood

Participant No: 5

Wat hebben we gedaan?

(schrijf / teken / vertel)

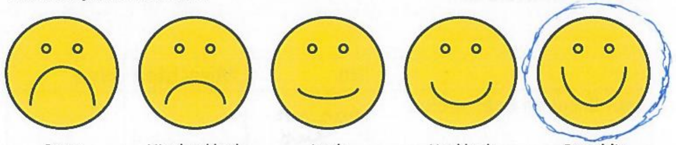


Round 2 blauw

Participant No: 6

Hoe leuk vond je Breuken Boer?

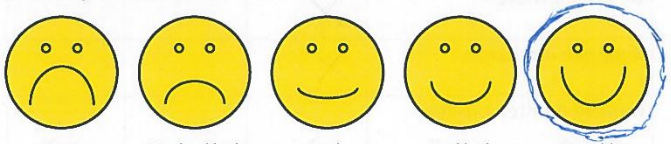
Omcirkel jouw antwoord



Stom | Niet heel leuk | Leuk | Heel leuk | Geweldig

Hoe leuk vond je het om opdrachten met Breuken Boer te doen?

Omcirkel jouw antwoord



Stom | Niet heel leuk | Leuk | Heel leuk | Geweldig

Participant No: ________

Zou je het nog een keer willen doen?

Vink jouw antwoord aan

	Ja	Misschien	Nee
Met Breuken Boer spelen	nog een keer		
Een opdracht oplossen	nog een keer		
Voedsel munten verdelen	[illegible]	X	
De dieren voeren	X		
Knoppen indrukken	X		
Nieuwe munten pakken		X	
Een nieuwe opdracht pakken	X		

Round 2 blauw 10

Participant No: 6

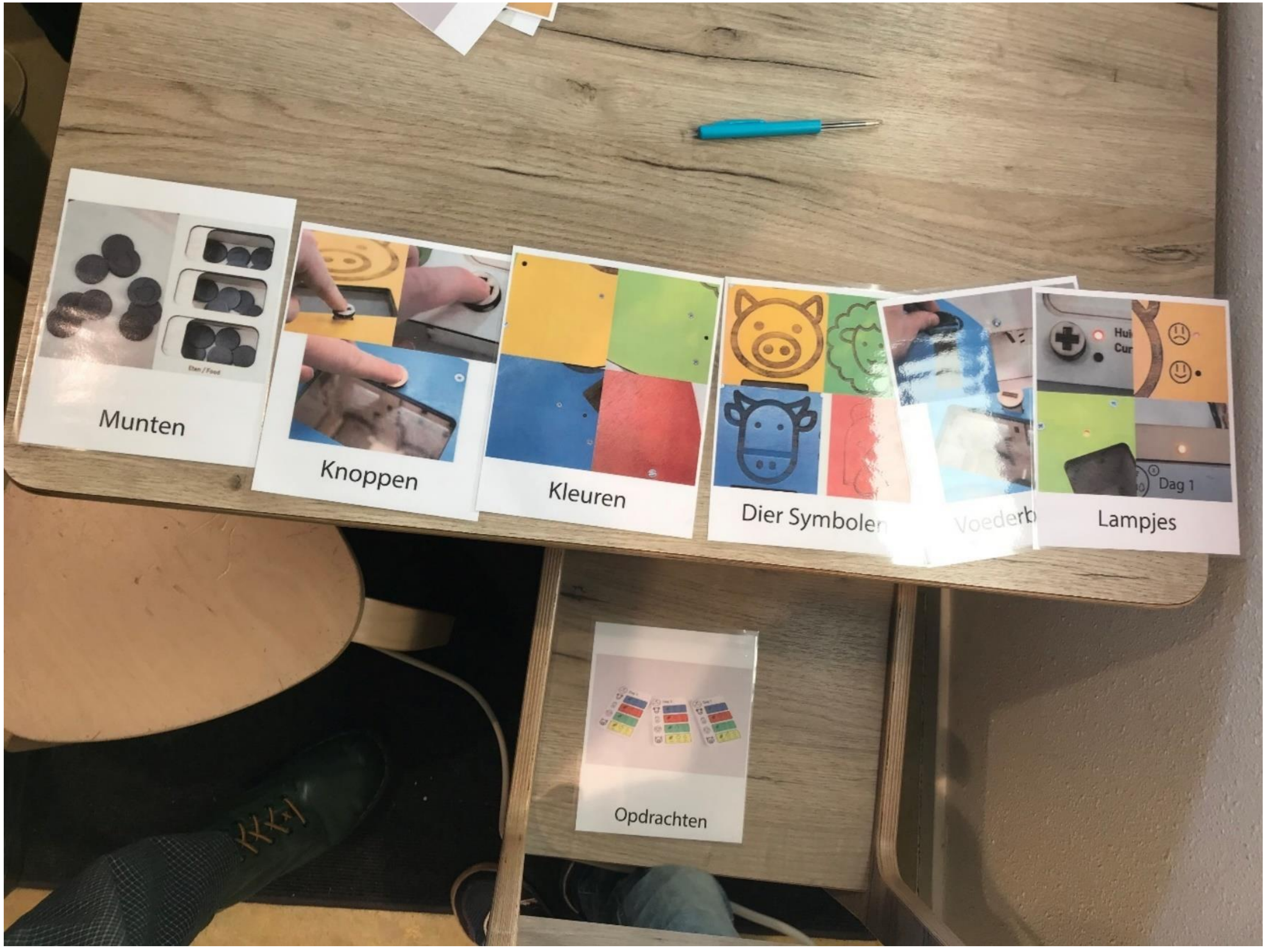
Wat hebben we gedaan?

(schrijf / teken / vertel)

F: CARD SORTING RESULTS

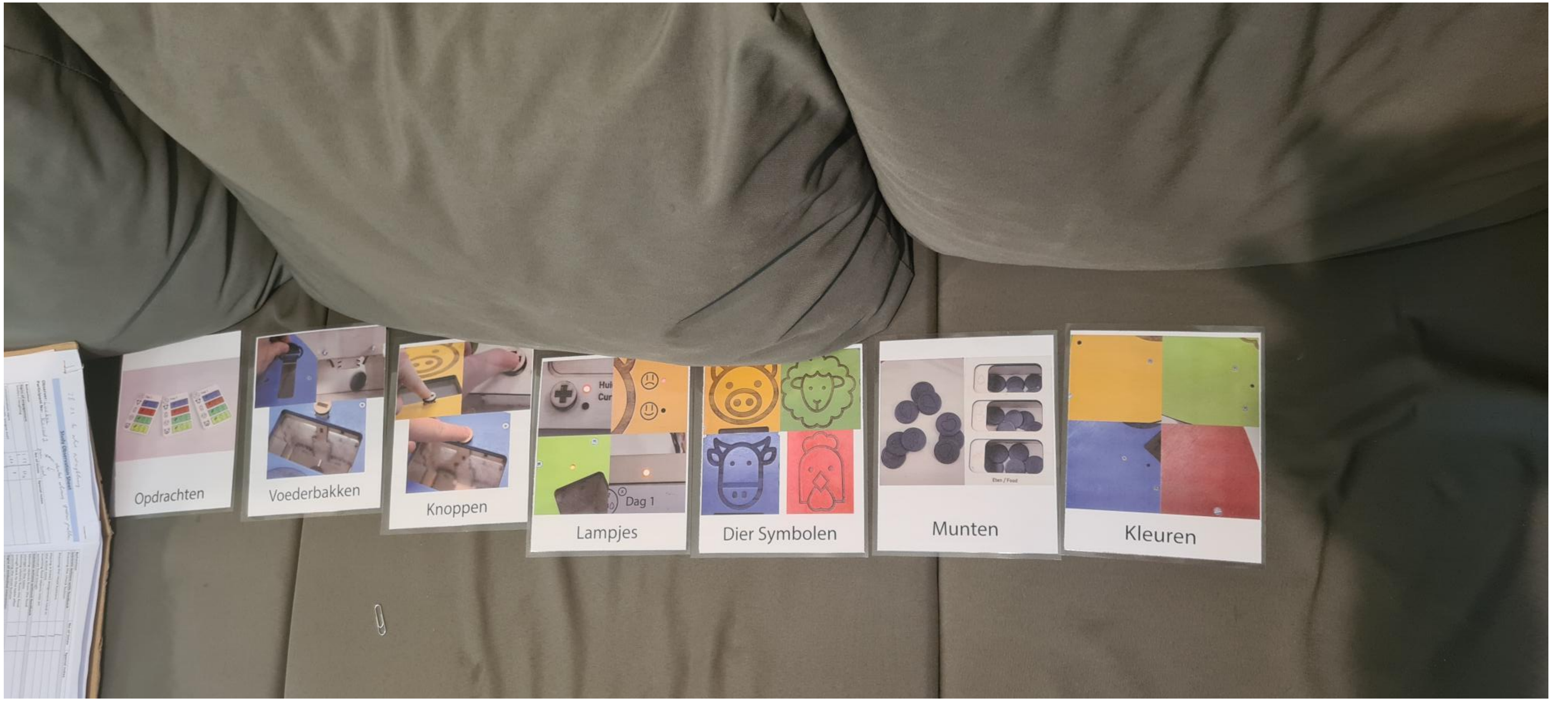
Participant 1

Participant 2



Participant 3

Participant 5



Participant 6

G: TABLE OF INTERVIEW RESULTS

Questions	Participants							
Smile-o-Meter	1	2	3	4	5	6	7	8
Hoe leuk vond je Breuken Boer? / How fun was Fraction Farm?	Geweldig / Brilliant	Geweldig / Brilliant	Geweldig / Brilliant	Geweldig / Brilliant	Geweldig / Brilliant	Geweldig / Brilliant	/	/
Hoe leuk vond je het om opdrachten met Breuken Boer te doen? / How fun was it to do assignments with Fraction Farm?	Geweldig / Brilliant	Heel leuk / Really fun	Geweldig / Brilliant	Leuk / Fun	Geweldig / Brilliant	Geweldig / Brilliant	/	/
Again-Again table								
Met Breuken Boer spelen / Play with Fraction Farm	Ja / Yes	Ja / Yes	Ja / Yes	Ja / Yes	Ja / Yes	Ja / Yes	/	/
Een opdracht oplossen / Solve an assignment	Ja / Yes	Ja / Yes	Ja / Yes	Ja / Yes	Misschien / Maybe	Ja / Yes	/	/
Voedsel munten / Distribute food coins	Ja / Yes	Ja / Yes	Ja / Yes	Ja / Yes	Ja / Yes	Misschien / Maybe	/	/
De dieren voeren / Feed the animals	Ja / Yes	Ja / Yes	Ja / Yes	Ja / Yes	Ja / Yes	Ja / Yes	/	/
Knoppen indrukken / Press buttons	Ja / Yes	Ja / Yes	Ja / Yes	Ja / Yes	Ja / Yes	Ja / Yes	/	/
Nieuwe munten / Take new coins	Misschien / Maybe	Misschien / Maybe	Ja / Yes	Ja / Yes	Ja / Yes	Misschien / Maybe	/	/
Een nieuwe opdracht pakken / Take a new assignment	Misschien / Maybe	Ja / Yes	Ja / Yes	Ja / Yes	Ja / Yes	Ja / Yes	/	/
Card Sorting								
Meest leuk / Most fun	Opdrachten / Assignments	Opdrachten / Assignments	Munten / Coins	/	Dier Symbolen / Animal Icons	Dier Symbolen / Animal Icons	/	/
	Voederbakken / Feeding troughs	Dier Symbolen / Animal Icons	Knoppen / Buttons	/	Lampjes / Lights	Kleuren / Colors	/	/
	Knoppen / Buttons	Voederbakken / Feeding troughs	Kleuren / Colors	/	Kleuren / Colors	Opdrachten / Assignments	/	/
	Lampjes / Lights	Munten / Coins	Dier Symbolen / Animal Icons	/	Voederbakken / Feeding troughs	Voederbakken / Feeding troughs	/	/
	Dier Symbolen / Animal Icons	Knoppen / Buttons	Voederbakken / Feeding troughs	/	Opdrachten / Assignments	Munten / Coins	/	/
	Munten / Coins	Lampjes / Lights	Lampjes / Lights	/	Knoppen / Buttons	Knoppen / Buttons	/	/
Minst leuk / Least fun	Kleuren / Colors	Kleuren / Colors	Opdrachten / Assignments	/	Munten / Coins	Lampjes / Lights	/	/
Age	8	8	7	7	6 (bijna 7)	7	8 (zit in groep 4)	7

H: OBSERVATION ANALYSIS

Observation notes:

Most participants did not have experience with fraction concepts. In both groups there was only one participant who did have some experience with fractions.

A lot of interaction between participants:

- Positive; thinking together, helping each other, handing things to each other, waiting on others, asking others for help, giving instructions
- Negative; grabbing coins without asking ("participant 4 stole everything from me!"), pressing other people's buttons, not waiting on the rest, ignoring others' instructions

Especially in the 2nd round the participants were more focussed on just solving their part rather than working together to solve the whole. Participants did try to get others to listen, but they often got in each other's way. Objects were distributed a lot between participants.

Overall participants seemed very engaged; lots of positive vocalizations, concentration signs and laughter. Important to keep in mind is that taking part in these studies is seen as a fun and special activity by the children at the BSO, so the participants are already primed before they see the prototype. A fair amount of disengagement signs were also observed, especially when solving the difficult 3rd assignment, or when other participants were being obtrusive. However, participants still wanted to stay and solve the assignment, nobody wanted to quit, suggesting that they were still motivated to work with the prototype, despite getting frustrated.

In the 2nd round participants did not take time to reflect on the completed assignments (1 and 2) and just wanted to place the next assignment immediately.

Participants did not wait for an explanation and started playing around with the prototype immediately. Grabbing coins and inserting them seemed very intuitive as they did not require any instruction to start doing it, same with pressing the reset button. In round 2 participants wanted to try out what would happen if they put all the objects into one animals slot ("Can I put everything inside in one go?".

In the 1st round participant 1 acted somewhat as a leader and the participants worked together to solve the more difficult assignment. Participant 1 was able to reframe his understanding of fractions and then managed to help the others so that the overall assignment was correct.

When confronted with having to use mathematical thinking, participant 3 got a bit frustrated ("I don't feel like doing maths").

Some participants wanted to do the earlier assignments again.

Participants often identified themselves as the animals: “I am the chicken, so I need (…)”, and personified them: “I (the chicken) can’t get more apples, else I will get sick.”, “The sheep needs (…)”, “You’re the chicken, so you don’t need apples”.

Lot’s of pressing the check button. The participants seemed to want quick feedback on what they were doing; trial and error. Some participants were seen hitting the smiley icons, perhaps to change the color of the light. Participants tended to just test their ideas as fast as possible, as opposed to first laying their answer out physically on the table. Coins were just grabbed directly and then put in the slots, sometimes even from the food storage. The check button was often competed for by different participants (“No, I want to press the button!”), as they each individually wanted to know if what they did was correct.

Participants who were done faster (worked quicker / had an easier assignment) showed signs of boredom (participant 2, “because this is taking so long, I’m going to go to the toilet”), however this also led to them trying to engage with what the other participants were doing and try to solve / help solve others’ tasks (for example, when participant 2 saw that her part was correct and the others were still struggling, she started looking at what participant 1 was doing and tried to help).

Participant 5 tried to solve assignment 3 by first doing it the way he thought was correct and then seeing what was left on the table.

Participants would get frustrated when they could not solve the more difficult assignment, leading to disengagement at times.

When the methods they applied in assignment 1 and 2 (just looking at the numerator and inserting that amount) did not work for assignment 3 (as the denominator no longer matched the amount of objects), participant 6’s first reaction was to say that “It’s broken!”. Other participants also made similar remarks “What did I do wrong?”.

With assignment 3, the chicken and the pig were solved easily, as they would be correct when applying the numerator strategy (just like assignment 1 and 2). Participants then tried to figure out what went wrong with the other 2, and were reluctant to touch the objects that they had put inside the chicken and the pig (as those were already correct).

During assignment 3, participants started distributing the objects on the table more, instead of inserting them immediately (but only after testing their initial answers quickly a couple times).

Participants had to be reminded that the corner of the assignment cards tells what amount of each object needs to be on the table.

All participants were asked to rate the prototype from 1 to 10. All of them rated with a 10 (which is to be expected, taking part in a user study is a special activity for the children and tends to be seen as fun and exciting by them).

When drawing what they had done, almost all of the participants drew the round table first, and then the animal icons, then the side table. Only 3 participants also drew the smileys, 3 drew the food troughs, and only 1 drew the coins.

Regarding embodied interactions, participants did a lot of exploration of the objects and their affordances, which aligned with their trial and error approach. Objects were regularly divided by their type. In group 1 participants arranged all the necessary objects on the middle of the table, and then divided them over the different animals. These participants often shared objects between each other. In group 2 the participants got more in each other's way, preventing them from functionally sharing and arranging the objects between each other. As group 2 did not manage to solve assignment 3 by themselves, one of the observers gave them a visual explanation of what 1/3rd of 6 is, by taking 6 objects and dividing it into 3 groups of 2. After this, participant 7 applied this same method to solve the assignment.

Participant 8, who already had learnt some about fractions in school, tried to explain fractions by drawing a cake with her fingers on the table, dividing it in 4 pieces. A design feature that could be implemented is to recreate this pie model on the table, by having rings divided into different fractions on the table. Students could use this to evenly divide the objects over the different parts of a ring, connecting Fraction Farm to the pie model.

Height and size of the table seemed to be right, children could easily reach everything and could use the prototype both whilst standing and sitting on a small chair.

Notes about study design:

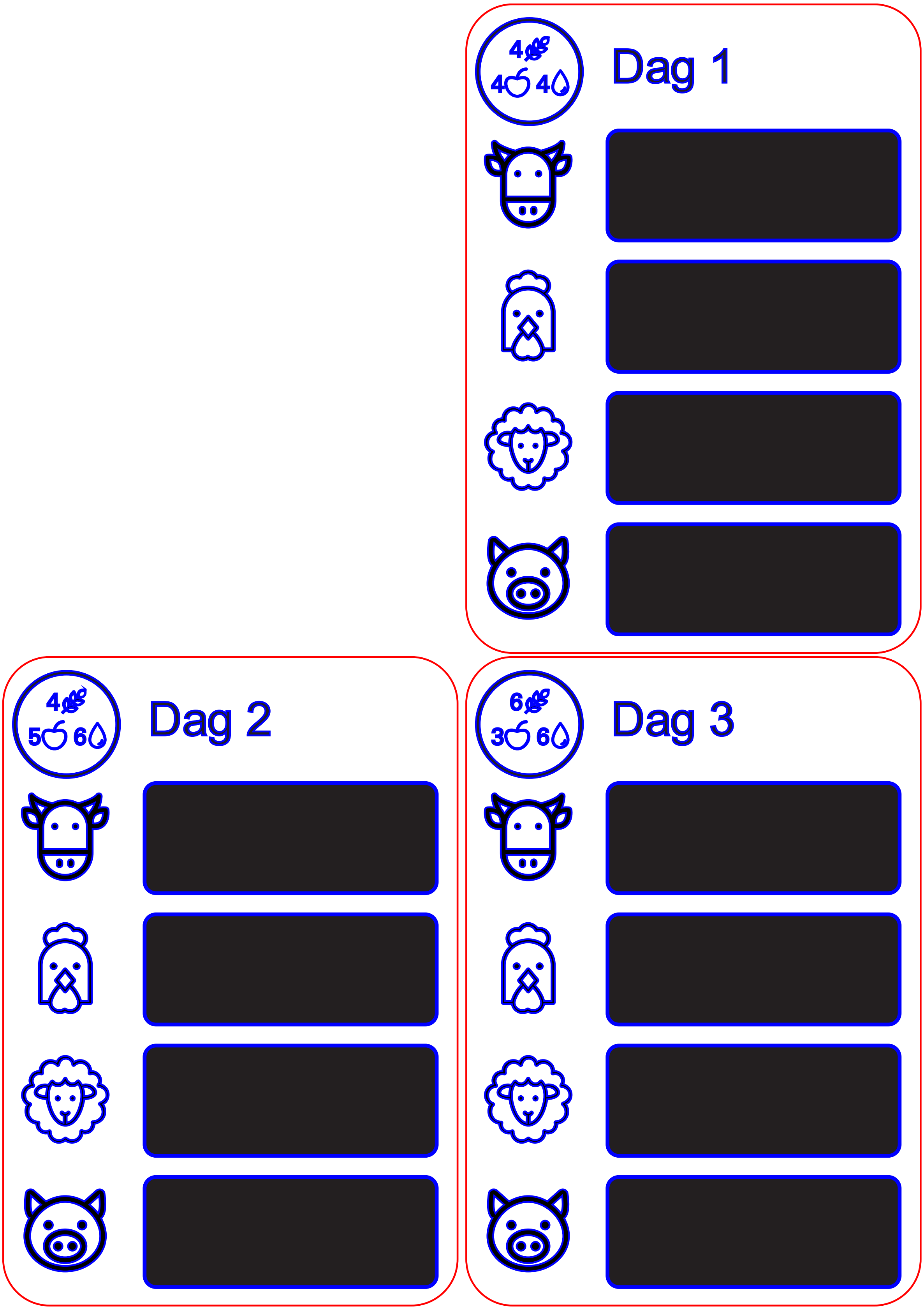
All observations should be made on 1 sheet in front of the observer. Having to flip the sheet up to make notes for another participant does not work.

Most participants struggled with reading a lot, most interview questions had to be verbally asked to the participants.

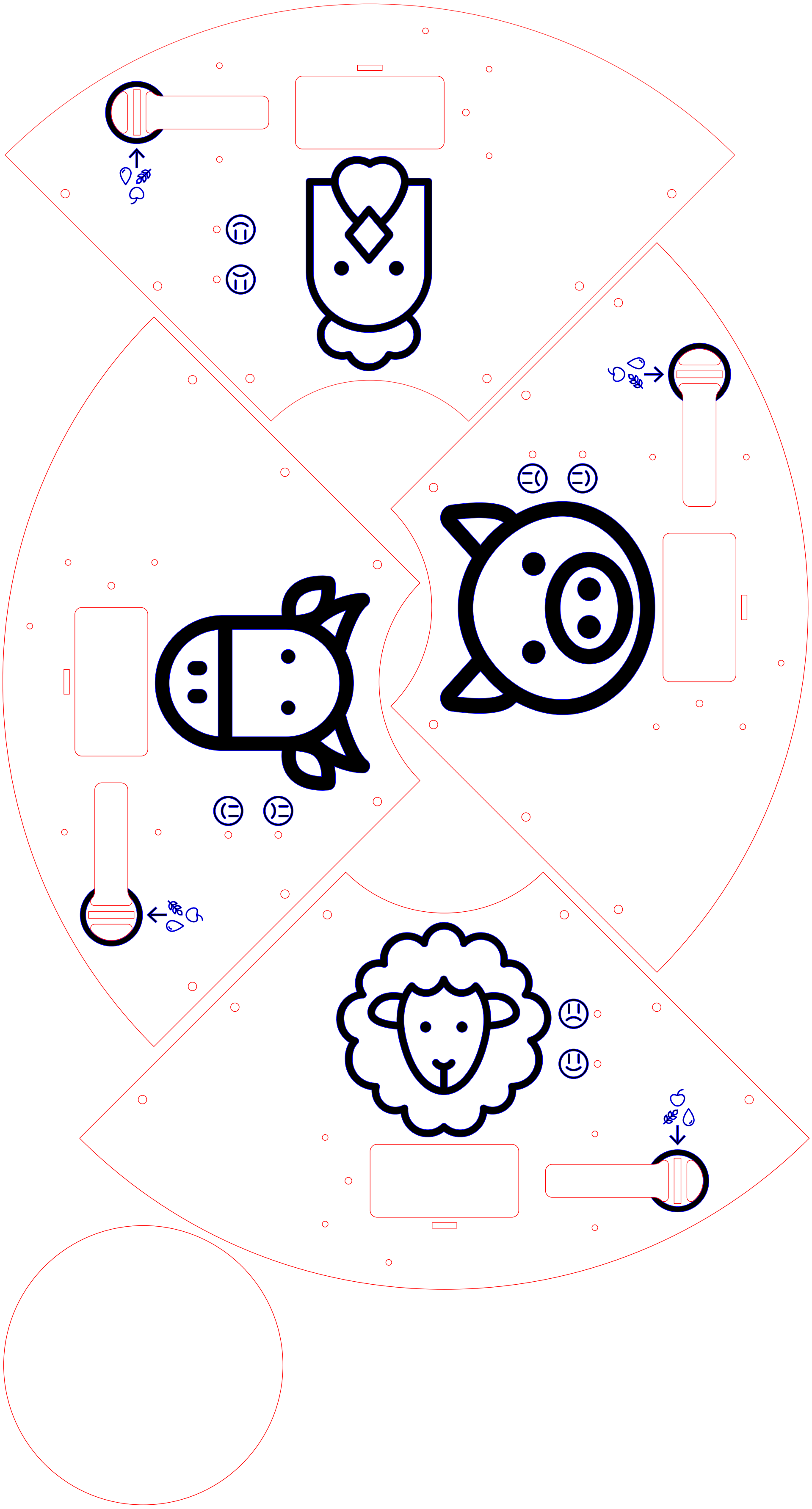
Time constraints! The study was probably a bit too long (45+ minutes), participants struggled with concentrating on the interview questions / tasks. Next studies should probably have clearer focus, either mainly observations in a more structured and focussed way, ideally with recordings, or mainly interviews with shorter interaction time / structured break.

Space limitations for the card sorting, sorting 7 big cards takes up space and the room was a bit too small. On top of this, 7 cards might be too many. Most participants said that they found all parts enjoyable (so the actual distinction between the top of the list and the bottom might not be so large). The activity also requires a decent amount of concentration, so having each session take so long was also not beneficial for this task. For this reason it was also chosen to not also ask them to rank the card based on what they remembered the most (also because they were in the room with the prototype, and ranking on enjoyability already points to remembrance somewhat).

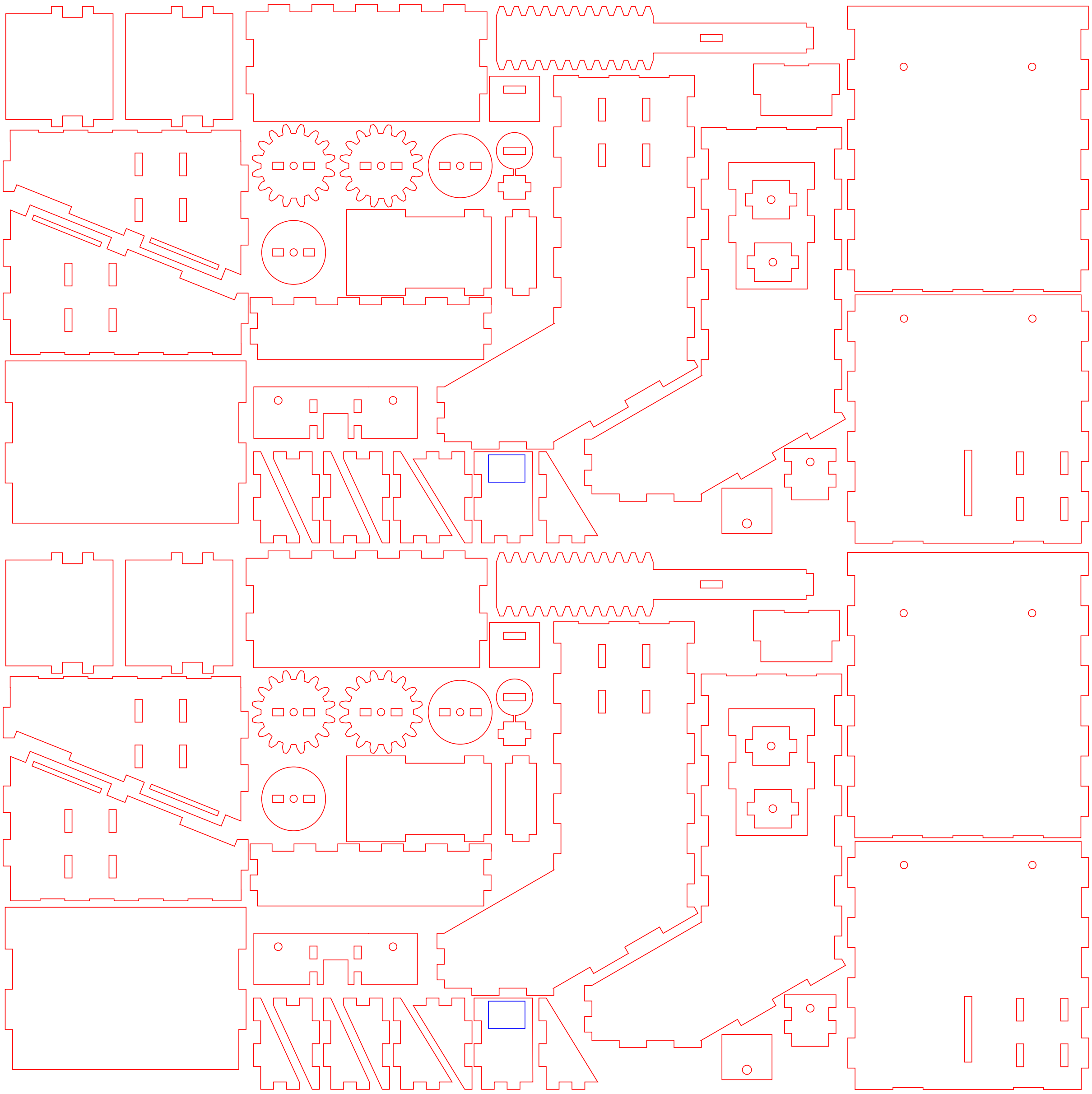
I: ASSIGNMENT CARD LASERCUTTING FILE



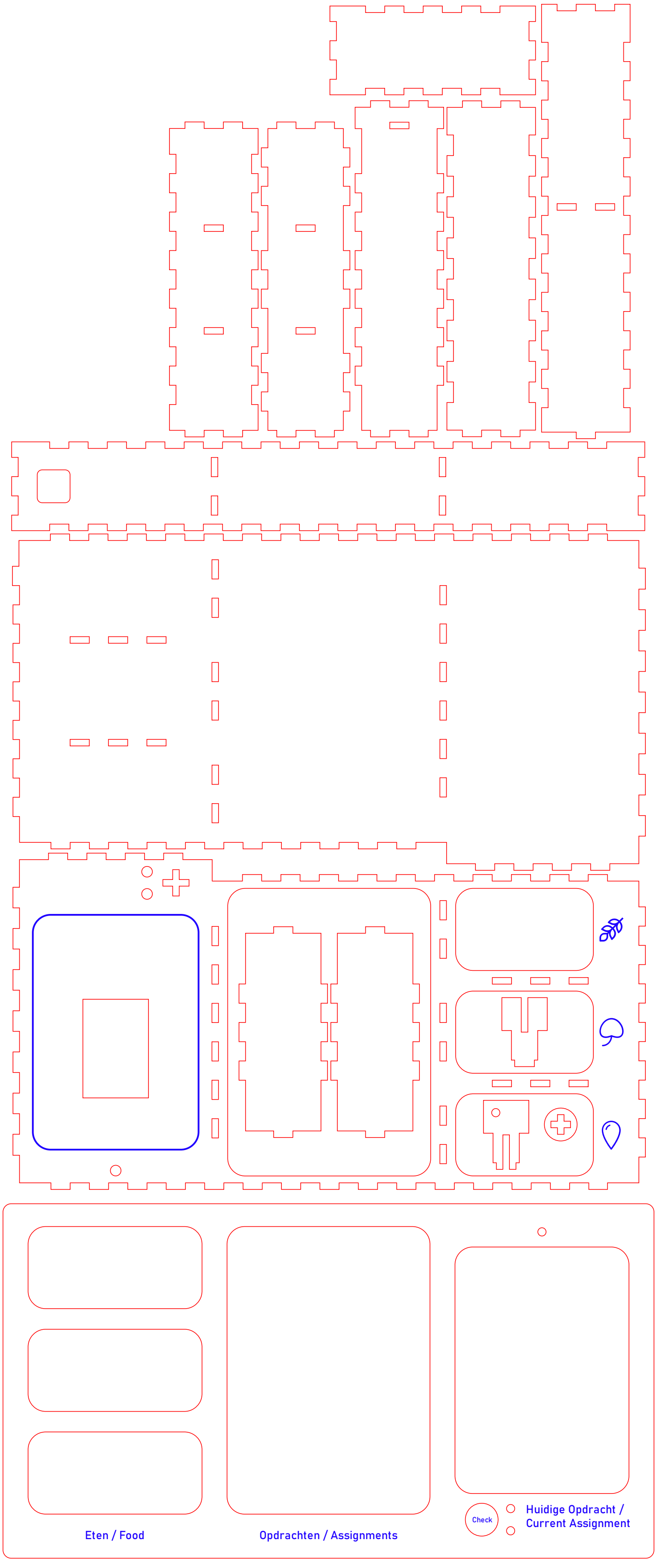
J: ANIMAL ZONES LASERCUTTING FILE



K: OBJECT DEPOSIT LASERCUTTING FILE



L: SIDETABLE LASERCUTTING FILE



M: ARDUINO UNO CODE

For interfacing with the MFRC522 modules, a library by Miguel Balboa was used. The library can be found here: `https://github.com/miguelbalboa/rfid`

```
#include <SPI.h>
#include <MFRC522.h>
#include <Wire.h>
#include <millisDelay.h>
#include <PinFlasher.h>

#define RST_PIN 9  // Configurable, see typical pin layout above
#define SS_PIN 10  // Configurable, take a unused pin, only HIGH/LOW required

#define CHECK_PIN 4

#define YLED_PIN 7
#define GLED_PIN 6
#define RLED_PIN 5


MFRC522 mfrc522(SS_PIN, RST_PIN);  // Create MFRC522 instance.

// Create the arrays that store all the uids linked to each object type

byte assignments[3][4] = {
  { 0x63, 0x28, 0x5B, 0xAD },
  { 0x63, 0x97, 0x53, 0xAC },
  { 0x23, 0x5D, 0x74, 0xAD }
};

byte newassignments[3][4] = {
  { 0xBD, 0x73, 0xD4, 0xDF },
  { 0xDD, 0x75, 0xD4, 0xDF },
  { 0x1D, 0x76, 0xD4, 0xDF }
};

int answers[3][3][4] = {
  //ch, co, p, s,
  { { 1, 1, 1, 1 },
    { 0, 2, 1, 1 },
    { 1, 1, 1, 1 } },  // assignment 1
  { { 1, 1, 1, 1 },
    { 1, 2, 1, 1 },
    { 1, 2, 1, 2 } },  // assignment 2
  { { 1, 2, 2, 1 },
    { 0, 1, 1, 1 },
    { 1, 2, 2, 1 } }  // assignment 3
};
```

```
int count[3][4] = {
  { 0, 0, 0, 0 },
  { 0, 0, 0, 0 },
  { 0, 0, 0, 0 }
};

int assignmentAct = -1;
int assignmentPrev = -2;
int checkVal = -1;
int prevVal = -1;

PinFlasher yLedFlash(YLED_PIN);
millisDelay blinkDelay;
bool blinking;
millisDelay checkDelay;

/**
 * Initialize.
 */
void setup() {

  Serial.begin(9600);  // Initialize serial communications with the PC
  while (!Serial)
    ;  // Do nothing if no serial port is opened (added for Arduinos based on
ATMEGA32U4)

  Wire.begin();
  SPI.begin();  // Init SPI bus

  pinMode(CHECK_PIN, INPUT_PULLUP);

  pinMode(YLED_PIN, OUTPUT);
  pinMode(GLED_PIN, OUTPUT);
  pinMode(RLED_PIN, OUTPUT);

  mfrc522.PCD_Init();
  mfrc522.PCD_DumpVersionToSerial();

  blinking = false;
}


/**
 * Main loop.
 */
void loop() {
  int index = 0;
  Wire.requestFrom(11, 6);
```

```
while (Wire.available() > 0 & index < 6) {
  for (int i = 0; i < 3; i++) {
    for (int j = 0; j < 2; j++) {
      int incData = Wire.read();
      count[i][j] = incData;
      index++;
    }
  }
}
index = 0;
Wire.requestFrom(12, 6);
while (Wire.available() > 0 & index < 6) {
  for (int i = 0; i < 3; i++) {
    for (int j = 2; j < 4; j++) {
      int incData = Wire.read();
      count[i][j] = incData;
      index++;
    }
  }
}

checkVal = digitalRead(CHECK_PIN);
if (checkVal == 0 && checkVal != prevVal) {
  bool complete = true;
  int cZones[4] = { 1, 1, 1, 1 };
  for (int j = 0; j < 4; j++) {
    for (int i = 0; i < 3; i++) {
      if (count[i][j] != answers[assignmentAct][i][j]) {
        complete = false;
        cZones[j] = 0;
        Serial.print(F("Incorrect answer for zone: "));
        Serial.println(j);
        break;
      }
    }
  }
  Wire.beginTransmission(11);
  Wire.write(5);
  Wire.write(cZones[0]);
  Wire.write(cZones[1]);
  Wire.endTransmission();
  Wire.beginTransmission(12);
  Wire.write(5);
  Wire.write(cZones[2]);
  Wire.write(cZones[3]);
  Wire.endTransmission();
  checkDelay.start(10000);
  if (complete) {
```

```
      Serial.println(F("Correct answer!"));
      digitalWrite(GLED_PIN, HIGH);
      digitalWrite(RLED_PIN, LOW);
    } else {
      digitalWrite(RLED_PIN, HIGH);
      digitalWrite(GLED_PIN, LOW);
    }
  }
  prevVal = checkVal;

  if (checkDelay.justFinished()) {
    digitalWrite(GLED_PIN, LOW);
    digitalWrite(RLED_PIN, LOW);
  }

  if (blinkDelay.justFinished()) {
    blinking = false;
    yLedFlash.setOnOff(PIN_ON);
  } else if (blinking) {
    yLedFlash.setOnOff(40);
  }

  // Reset the loop if no new card present on the sensor/reader. This saves
the entire process when idle.
  if (!mfrc522.PICC_IsNewCardPresent()) {
    return;
  }

  // Select one of the cards
  if (!mfrc522.PICC_ReadCardSerial()) {
    return;
  }

  for (int i = 0; i < 3; i++) {
    if (check_object_type(mfrc522.uid.uidByte, assignments[i], 4)) {
      assignmentAct = i;
      break;
    }
  }

  if (assignmentAct != assignmentPrev) {
    blinkDelay.start(400);
    blinking = true;
  }
  assignmentPrev = assignmentAct;
}


/**
```

```
 * Helper routine to dump a byte array as hex values to Serial.
 */
void dump_byte_array(byte* buffer, byte bufferSize) {
  for (byte i = 0; i < bufferSize; i++) {
    Serial.print(buffer[i] < 0x10 ? " 0" : " ");
    Serial.print(buffer[i], HEX);
  }
}

// Checks whether the input uid matches a uid from the chosen object type
bool check_object_type(byte* inputObject, byte* objectType, byte uidSize) {
  bool objectMatch = true;
  for (int i = 0; i < uidSize; i++) {
    if (inputObject[i] != objectType[i]) {
      objectMatch = false;
      break;
    }
  }
  return objectMatch;
}
```

N: ARDUINO NANO CODE

```
#include <SPI.h>
#include <MFRC522.h>
#include <Wire.h>
#include <millisDelay.h>
#include <PinFlasher.h>

#define RST_PIN 10
#define SS_1_PIN 9
#define SS_2_PIN 8

#define COW_GLED_PIN 7
#define COW_RLED_PIN 6
#define COW_YLED_PIN A1
#define CHICKEN_GLED_PIN 4
#define CHICKEN_RLED_PIN 3
#define CHICKEN_YLED_PIN A0

#define COW_RST_PIN 5
#define CHICKEN_RST_PIN 2

#define NR_OF_READERS 2

byte ssPins[] = { SS_1_PIN, SS_2_PIN };

MFRC522 mfrc522[NR_OF_READERS];  // Create MFRC522 instance.

// Create the arrays that store all the uids linked to each object type
const int nrOfUIDS = 6;

const byte grains[nrOfUIDS][4] = {
  { 0x5D, 0x76, 0xD4, 0xDF },
  { 0x4D, 0x66, 0xD4, 0xDF },
  { 0x8D, 0x64, 0xD4, 0xDF },
  { 0xBD, 0x6A, 0xD4, 0xDF },
  { 0xFD, 0x6A, 0xD4, 0xDF },
  { 0x3D, 0x6B, 0xD4, 0xDF }
};

const byte fruits[nrOfUIDS][4] = {
  { 0xBD, 0x73, 0xD4, 0xDF },
  { 0x7D, 0x6B, 0xD4, 0xDF },
  { 0x9D, 0x6D, 0xD4, 0xDF },
  { 0xDD, 0x6D, 0xD4, 0xDF },
  { 0x1D, 0x6E, 0xD4, 0xDF },
  { 0x5D, 0x6E, 0xD4, 0xDF }
};
```

```
const byte water[nrOfUIDS][4] = {
  { 0xDD, 0x75, 0xD4, 0xDF },
  { 0x9D, 0x6C, 0xD4, 0xDF },
  { 0xCD, 0x72, 0xD4, 0xDF },
  { 0x0D, 0x73, 0xD4, 0xDF },
  { 0x3D, 0x73, 0xD4, 0xDF },
  { 0x7D, 0x73, 0xD4, 0xDF }
};

byte prevuid[2][4];

int count[3][2] = {
  { 0, 0 },
  { 0, 0 },
  { 0, 0 }
};

int coprevVal = -1;
int chprevVal = -1;
int coFoodStored = 0;
int chFoodStored = 0;

PinFlasher cowyLedFlash(COW_YLED_PIN);
PinFlasher chyLedFlash(CHICKEN_YLED_PIN);
millisDelay cowBlinkDelay;
millisDelay chBlinkDelay;
bool cowBlinking;
bool chBlinking;
millisDelay checkDelay;

/**
 * Initialize.
 */
void setup() {

  Serial.begin(9600);  // Initialize serial communications with the PC
  Wire.begin(11); - The other Arduino Nano writes to 12 instead
  while (!Serial)
    ;  // Do nothing if no serial port is opened (added for Arduinos based on
ATMEGA32U4)

  SPI.begin();  // Init SPI bus

  pinMode(COW_GLED_PIN, OUTPUT);
  pinMode(COW_RLED_PIN, OUTPUT);
  pinMode(COW_YLED_PIN, OUTPUT);
  pinMode(CHICKEN_GLED_PIN, OUTPUT);
  pinMode(CHICKEN_RLED_PIN, OUTPUT);
```

```
  pinMode(CHICKEN_YLED_PIN, OUTPUT);

  pinMode(COW_RST_PIN, INPUT_PULLUP);
  pinMode(CHICKEN_RST_PIN, INPUT_PULLUP);

  for (uint8_t reader = 0; reader < NR_OF_READERS; reader++) {
    mfrc522[reader].PCD_Init(ssPins[reader], RST_PIN);  // Init each MFRC522
card
    Serial.print(F("Reader "));
    Serial.print(reader);
    Serial.print(F(": "));
    mfrc522[reader].PCD_DumpVersionToSerial();
  }

  Wire.onRequest(writeCount);
  Wire.onReceive(executeCommand);
}

/**
 * Main loop.
 */
void loop() {

  int cowVal = digitalRead(COW_RST_PIN);
  int chickenVal = digitalRead(CHICKEN_RST_PIN);
  if (cowVal == 0 && cowVal != coprevVal) {
    Serial.println("resetting cow");
    for (int i = 0; i < 3; i++) {
      count[i][0] = 0;
    }
    coFoodStored = 0;
    for (int i = 0; i < 4; i++) {
      prevuid[0][i] = 0x00;
    }
  }
  coprevVal = cowVal;
  if (chickenVal == 0 && chickenVal != chprevVal) {
    Serial.println("resetting chicken");
    for (int i = 0; i < 3; i++) {
      count[i][1] = 0;
    }
    chFoodStored = 0;
    for (int i = 0; i < 4; i++) {
      prevuid[1][i] = 0x00;
    }
  }
  chprevVal = chickenVal;
```

```
  if (coFoodStored == 1) {
    if (cowBlinkDelay.justFinished()) {
      cowBlinking = false;
      cowyLedFlash.setOnOff(PIN_ON);
    } else if (cowBlinking) {
      cowyLedFlash.setOnOff(40);
    }
  } else {
    cowyLedFlash.setOnOff(PIN_OFF);
  }
  if (chFoodStored == 1) {
    if (chBlinkDelay.justFinished()) {
      chBlinking = false;
      chyLedFlash.setOnOff(PIN_ON);
    } else if (chBlinking) {
      chyLedFlash.setOnOff(40);
    }
  } else {
    chyLedFlash.setOnOff(PIN_OFF);
  }

  if (checkDelay.justFinished()) {
    digitalWrite(COW_GLED_PIN, LOW);
    digitalWrite(COW_RLED_PIN, LOW);
    digitalWrite(CHICKEN_GLED_PIN, LOW);
    digitalWrite(CHICKEN_RLED_PIN, LOW);
  }

  for (uint8_t reader = 0; reader < NR_OF_READERS; reader++) {

    // Look for new cards

    if (mfrc522[reader].PICC_IsNewCardPresent() &&
mfrc522[reader].PICC_ReadCardSerial()) {
      Serial.print(F("Reader "));
      Serial.print(reader);
      // Show some details of the PICC (that is: the tag/card)
      Serial.print(F(": Card UID:"));
      dump_byte_array(mfrc522[reader].uid.uidByte, mfrc522[reader].uid.size);
      Serial.println();
      Serial.print(F("PICC type: "));
      MFRC522::PICC_Type piccType =
mfrc522[reader].PICC_GetType(mfrc522[reader].uid.sak);
      Serial.println(mfrc522[reader].PICC_GetTypeName(piccType));

      // Prevent the double reading of a tag
      int foodType = -1;
```

```
      if (check_object_type(mfrc522[reader].uid.uidByte, prevuid[reader], 4)
== false) {
        // Check for object type
        for (byte j = 0; j < nrOfUIDS; j++) {
          if (check_object_type(mfrc522[reader].uid.uidByte, grains[j], 4)) {
            foodType = 0;
            break;
          } else if (check_object_type(mfrc522[reader].uid.uidByte, fruits[j],
4)) {
            foodType = 1;
            break;
          } else if (check_object_type(mfrc522[reader].uid.uidByte, water[j],
4)) {
            foodType = 2;
            break;
          }
        }

        for (byte i = 0; i < 4; i++) {
          prevuid[reader][i] = mfrc522[reader].uid.uidByte[i];
        }

        // Increase count for the active reader for the read object type
        if (foodType != -1) {
          count[foodType][reader]++;
          if (reader == 0) {
            coFoodStored = 1;
            cowBlinking = true;
            cowBlinkDelay.start(300);
          }
          if (reader == 1) {
            chFoodStored = 1;
            chBlinking = true;
            chBlinkDelay.start(300);
          }
        }
      }

      // Reset foodtype
      foodType = -1;
      // Print results for the active reader
      switch (reader) {
        case 0:
          Serial.println(F("COW"));
          break;
        case 1:
          Serial.println(F("CHICKEN"));
          break;
```

```
      }

      Serial.println(F("grains: "));
      Serial.println(count[0][reader]);
      Serial.println(F("fruits: "));
      Serial.println(count[1][reader]);
      Serial.println(F("water: "));
      Serial.println(count[2][reader]);

      // Halt PICC
      mfrc522[reader].PICC_HaltA();
      // Stop encryption on PCD
      mfrc522[reader].PCD_StopCrypto1();
    }
  }
}

void writeCount() {
  for (int i = 0; i < 3; i++) {
    for (int j = 0; j < 2; j++) {
      Wire.write(count[i][j]);
    }
  }
}

void executeCommand(int bytes) {
  int data[3] = { -1, -1, -1 };
  int index = 0;
  while (Wire.available()) {
    int incData = Wire.read();
    data[index] = incData;
    index++;
  }

  if (data[0] == 11) {
    Serial.println(F("Reset command received"));
    Serial.println(F("Resetting count!"));
    for (int i = 0; i < 3; i++) {
      for (int j = 0; j < 2; j++) {
        count[i][j] = 0;
      }
    }
  }
  if (data[0] == 5) {
    Serial.println(F("check command received"));
    checkDelay.start(10000);
    Serial.print(F("Cow status: "));
    if (data[1] == 1) {
```

```
      Serial.println(F("correct"));
      digitalWrite(COW_GLED_PIN, HIGH);
      digitalWrite(COW_RLED_PIN, LOW);
    } else {
      Serial.println(F("incorrect"));
      digitalWrite(COW_RLED_PIN, HIGH);
      digitalWrite(COW_GLED_PIN, LOW);
    }
    Serial.print(F("Chicken status: "));
    if (data[2] == 1) {
      Serial.println(F("correct"));
      digitalWrite(CHICKEN_GLED_PIN, HIGH);
      digitalWrite(CHICKEN_RLED_PIN, LOW);
    } else {
      Serial.println(F("incorrect"));
      digitalWrite(CHICKEN_RLED_PIN, HIGH);
      digitalWrite(CHICKEN_GLED_PIN, LOW);
    }
  }
}


/**
 * Helper routine to dump a byte array as hex values to Serial.
 */
void dump_byte_array(byte* buffer, byte bufferSize) {
  for (byte i = 0; i < bufferSize; i++) {
    Serial.print(buffer[i] < 0x10 ? " 0" : " ");
    Serial.print(buffer[i], HEX);
  }
}

// Checks whether the input uid matches a uid from the chosen object type
bool check_object_type(byte* inputObject, byte* objectType, byte uidSize) {
  bool objectMatch = true;
  for (int i = 0; i < uidSize; i++) {
    if (inputObject[i] != objectType[i]) {
      objectMatch = false;
      break;
    }
  }
  return objectMatch;
}
```