Designing Physical Objects for Young Children's Magnitude Understanding: A TUI Research Through Design Journey

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ABSTRACT

Magnitude understanding, an understudied topic in Child-Computer Interaction, entails making nonsymbolic 'more-less' comparisons that influence young children's later math and academic achievements. To support this ability, designing tangible user interfaces (TUIs) demands considering many facets, ranging from elements within the physical world to the digital design components. This multifaceted activity brings many design decisions often not reflected in research. Therefore, we present this reflection via our research through design process in developing a vital design element, the physical form. We share our (i) physical object design criteria elicitation for magnitude understanding, (ii) hands-on making process, and (iii) preliminary studies with children engaging with objects. With our insights obtained through these steps, we project how this physical object-initiated research inspires the TUI in the upcoming steps and present design takeaways for CCI researchers.

Authors Keywords

Young children; Early math; Magnitude understanding; Tangible user interfaces; Research through design; Form

CSS Concepts

• Human-centered computing ~ Interaction design ~ Interaction design process and methods

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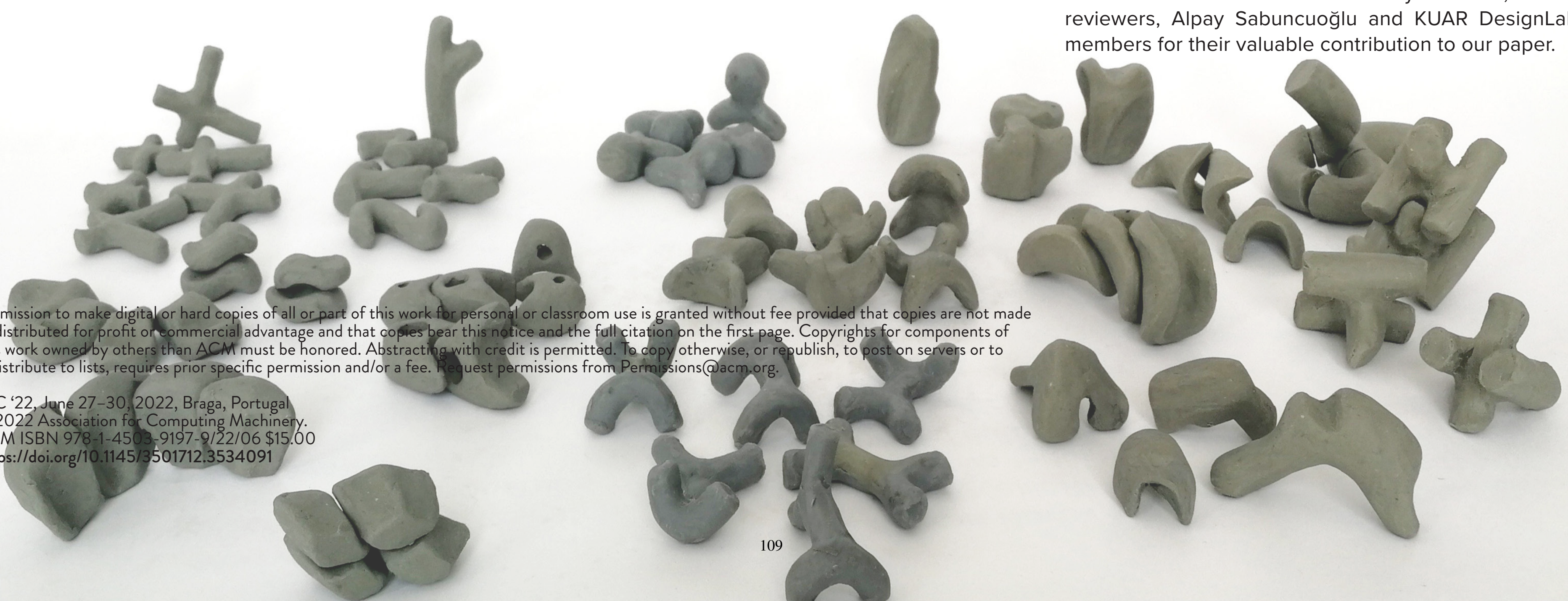

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INTRODUCTION

In this pictorial, we share a vital part of our *research through design* (RtD) journey that starts with the design process of physical objects for *magnitude understanding* (i.e., the ability to compare objects' as 'more than-less than'). We share insights from studies with young children (N=13) engaging with these objects that will guide the rest of our tangible user interface (TUI) design journey (Figure 1).

Our research is built on the importance of *early mathematics* development and the role of magnitude understanding within it. Early mathematics attainment drives a child's later academic achievements and relates to employment in STEAM (science, technology, engineering, arts, and math) disciplines [17,22]. Recent developmental studies state that *magnitude understanding* is essential for math skills and a broad range of cognitive abilities such as *spatial skills* [30]. Young children (ages 3-5) struggle with this ability, which entails *nonsymbolic 'more-less' comparisons* amongst objects. Hands-on experiences with different physical forms and spatial configurations could be fruitful for developing magnitude understanding [16,37].

What technology may bring to physical object-based learning is exemplified in tangible user interfaces (TUI) literature. TUIs embed computation into physical objects and surroundings, offering customized cues, self-directed discovery, and playful learning [15,27,35]. Regardless of physical objects' offerings for learning mathematics in general, digital technologies for math development accumulate around tablets [16]. Among the few studies on young children's math development through TUIs, the focus is generally on *symbolic math* skills (i.e., counting, partner numbers) [1,26,33]. Except for [6], to our knowledge, there are no TUIs for young children's magnitude understanding that help make up the other *nonsymbolic* facet of math development.

Besides this, the design process of TUIs is a multifaceted one. Several design elements demand careful consideration: physical objects, actions on objects, digital objects, informational relations, and learning activities [4]. The first two elements are mainly within the physical world, and the latter is related to the digital design components (e.g., couplings between physical and digital objects). The design process can start with any element by considering the educational and developmental needs. For our research, we followed a *physical object-initiated* process (Figure 1). We present our research steps as follows: (i) eliciting physical form design criteria for magnitude understanding, (ii) hands-on making process, and (iii) preliminary studies with children engaging with our research objects. Further, we provide *design takeaways* for CCI researchers towards designing TUIs for young children. With our insights obtained through these steps, we project how this physical object-initiated research inspires the design of the TUI for the upcoming steps.

Contrasting with previous TUI work on early math that dominantly employed traditional math objects [23,26,33], we designed novel objects for magnitude understanding. Without refuting the established practices in math object design, we probe its boundaries. In a broader sense, we argue that reconsidering what has been taken for granted from theory (e.g., reconsidering the design of math objects) is necessary for broadening the horizons in research [3,19]. This scrutiny into the given knowledge is vital for CCI, where the work is interdisciplinary and woven with theories.

Our work provides an account responding to the need to represent the complex processes involved in research through design [3,9,10,12]. We highlight the contribution of our work considering the physical form and the making process of TUIs as well as the design takeways for CCI researchers in similar pursuits. With a few exceptions, current design approaches for early education have user tests with finished prototypes[38]. Similarly, we observe that the decision-making process behind the physical objects in TUIs for young children and how particular features affect TUIs is often not reflected upon[36]. Although the physical form is only part of our main interest in developing a TUI for magnitude understanding, we stress that it is crucial in shaping how children use it. Previous research reveals that children may act on the physical objects afforded from their perspective, disregarding the digital feedback [14,21]. This urges us to be cautious about our assumptions about how designs will be used and the need to further involve children in the design research, especially before incorporating technologies.

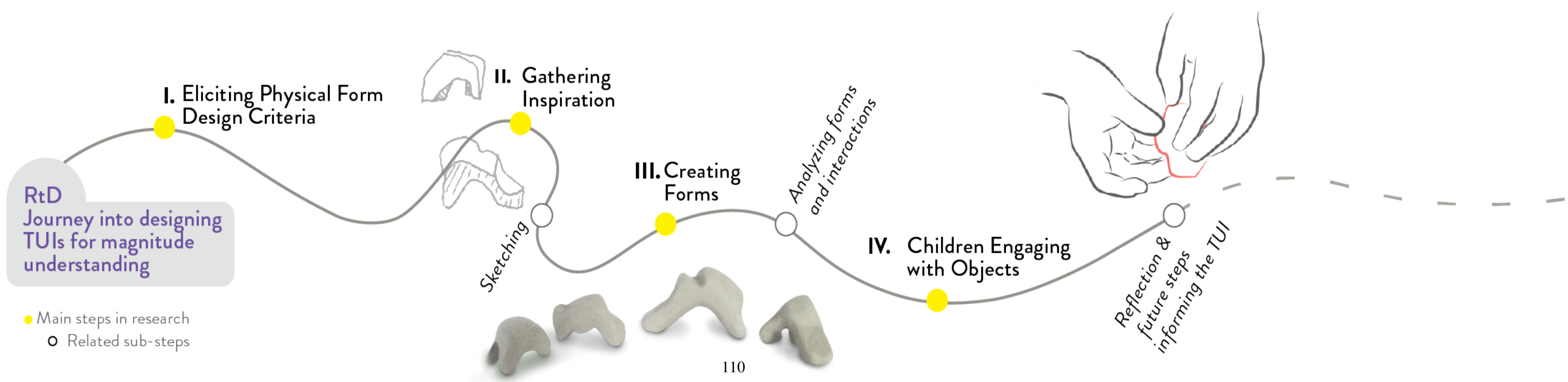


Figure 1. Snapshot of our research process.

DESIGN CRITERIA FOR MAGNITUDE UNDERSTANDING

Young children's magnitude understanding is related to their later math achievements and a range of skills like *spatial abilities* [17,22,29]. This ability entails 'more-less' comparisons amongst objects nonsymbolically (i.e., without the need to count). In example, deducing that five cherries are more than two elephants in terms of number. To date, there has not been a physical object set specifically for magnitude understanding. Therefore, we looked at developmental literature to guide our design criteria.

Physical objects employed in early math education are mostly traditional ones from the 19th century (i.e., Froebel Gifts, Montessori Beads, Cuisenaire Rods) or commercial tools like LEGO's [23,26,33]. These objects are designed to target counting and part-whole relations. However, a quick survey into the math-TUIs shows that they are research do not necessarily target these skills [1].

In sum, our physical form design criteria for magnitude understanding are: (i) non-salient , (ii) non-figurative, (iii) diverse, and (iv) spatially configurable physical forms. We explain these in detail below (Figure 2).

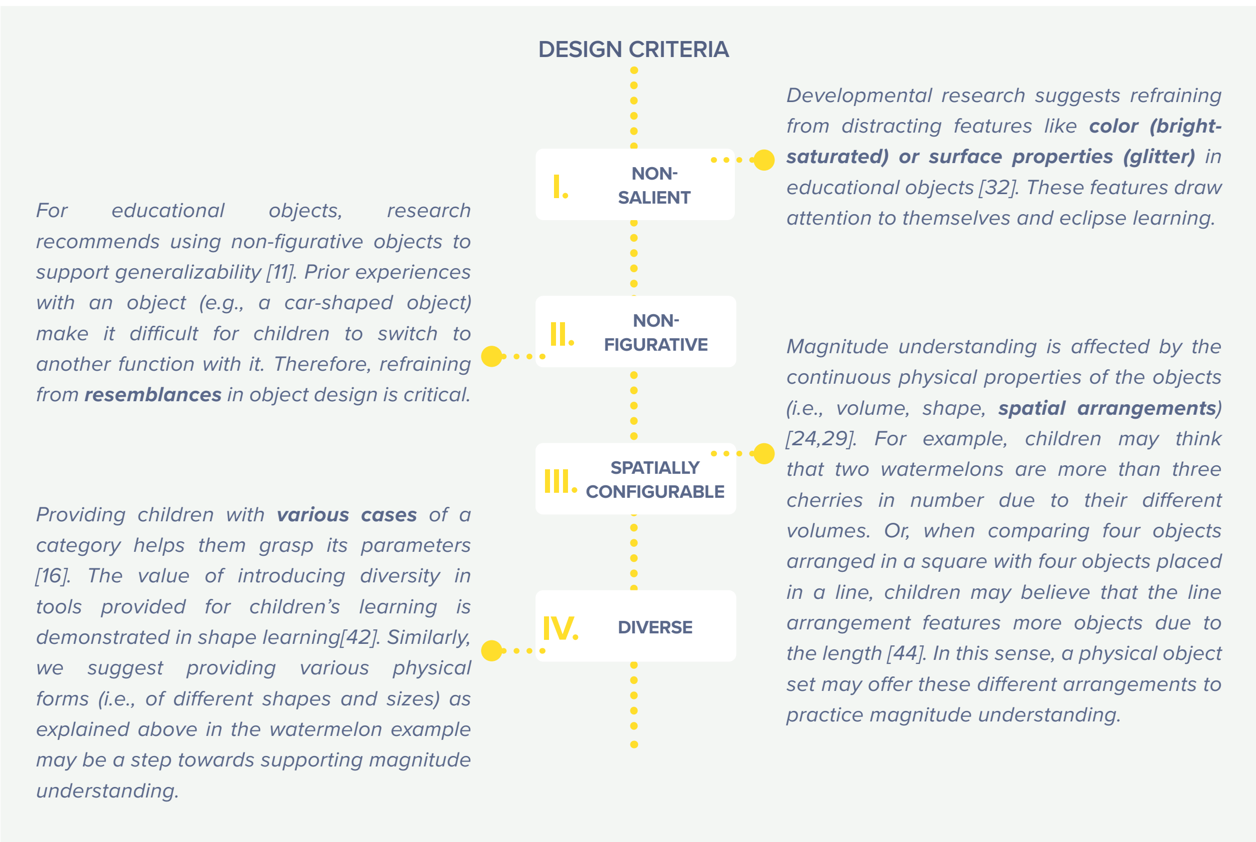


Figure 2. Physical object criteria

GATHERING INSPIRATION

We widened our creative palette before diving into the form creation process. Therefore, we looked at visual resources (e.g., sculptures, anatomy, engineering structures, etc.) and physical objects at our disposal (e.g., nature, fruits, etc.). While collecting inspiration, we used sketches (Figure 3) as a way of meaning-making [7]. Our inspiration-gathering process proceeded coincidentally, and we did not conduct a full inquiry.

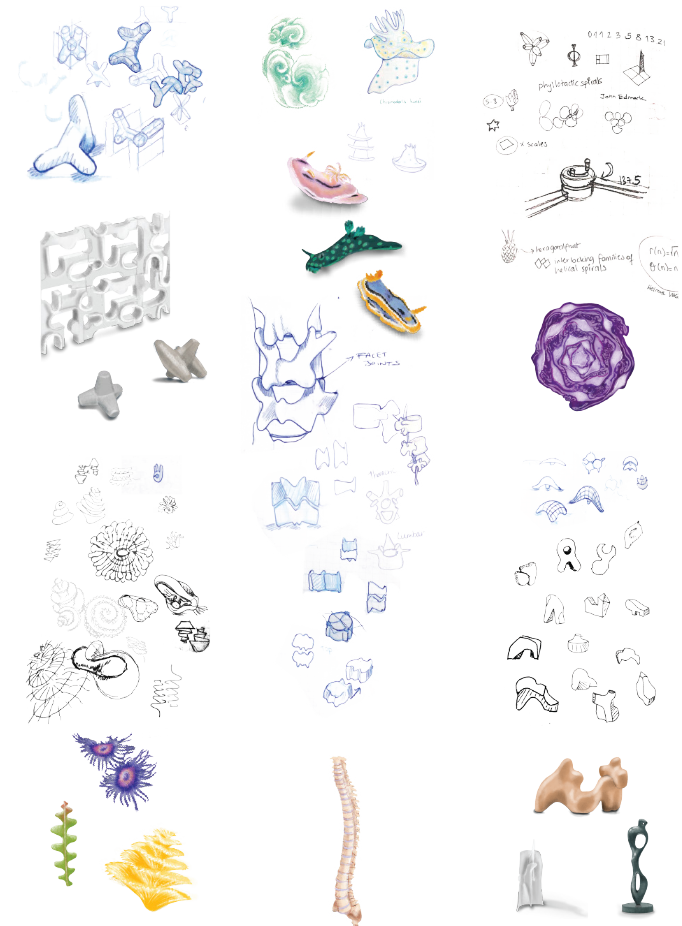


Figure 3. Inspiration sketches

CREATING PHYSICAL FORMS

We set out to design objects that embodied the four design criteria for our case study on magnitude understanding: (i) non-salient, (ii) non-figurative, (iii) spatially configurable, and (iv) diverse forms. Instead of creating forms that fulfilled all the design criteria, we thought of them separately or in conjunction. This was because thinking about all the requirements during creation put some pressure on our design process. We used plasticine material to prototype the forms due to its easy manipulation and non-drying properties. Overall, some forms arose from our earlier sketches, and some were spontaneous creations with the material.

Figure 4. Designed physical objects

Analyzing forms in relation to our design criteria
We reviewed each set, considering our design criteria for magnitude understanding: (i) non-saliency (min. color and texture), (ii) non-figurativeness, (iii) diverse and (iv) 3D- configurable forms within the set.

Since our designs refrained from color or texture, the first design criteria, we provide an analysis based on the other three criteria in the figures and our analysis process. Note that we refer to our reflections by analysis, not a strict procedure. Overall, we eliminated the objects that did not meet the design criteria from our perspective.

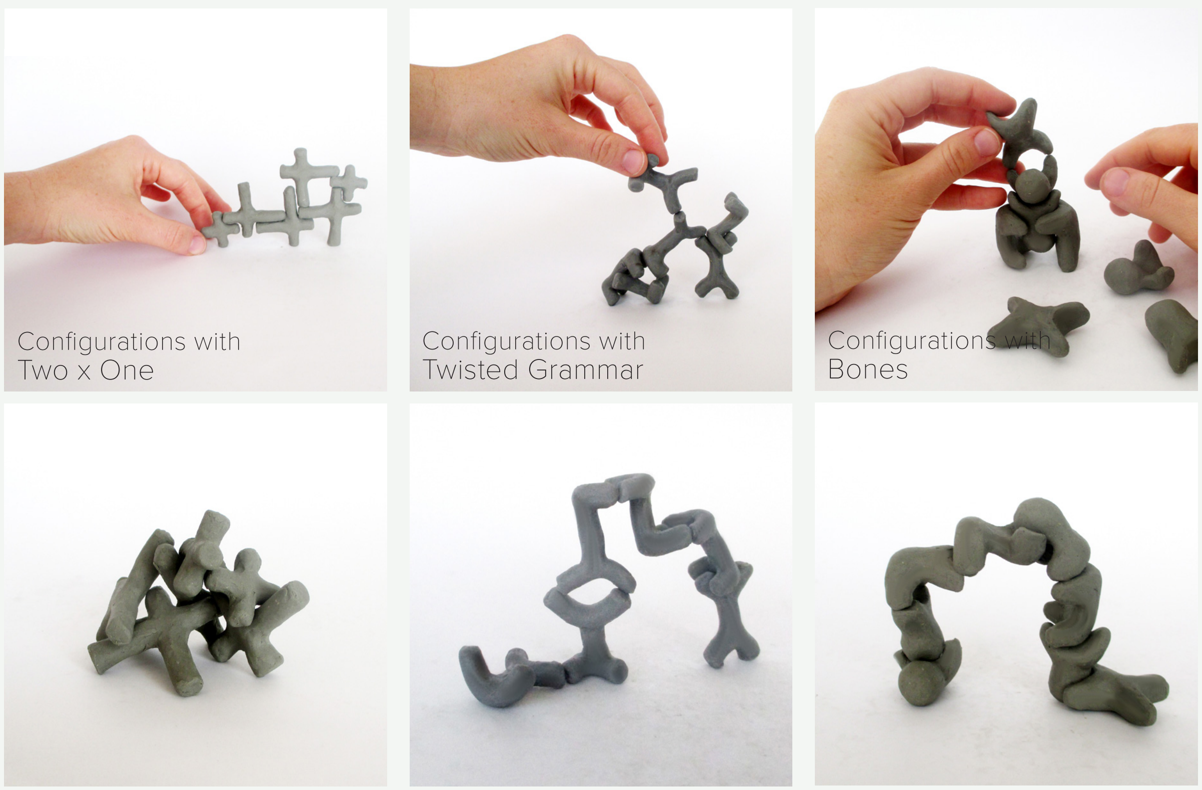


Figure 5. Configuration diversity analysis

Configuration diversity analysis

Forms that only enabled limited configurations (Figure 6, Fold, Alphabet, Spiral, Rise, Cut-outs) were unproductive. Therefore, the rest of the figures presented in this and the next page offer us a variety of configurations. When we mention configuring objects, interlocking features observed in LEGO's could come to mind. However, we realized that these facilitating approaches might result in a pitfall. For example, if we enable object configuration with LEGO-like notches, children might act on the objects as a construction kit due to their prior experiences [11]. We refrained from such supplementary form-configuration features in our designs.

Further, we realized piece-legibility was an important consideration in configurations. To explain, we realized that pieces were harder to see when object forms had greater flux. We refer to the extent of 'limbs growing out from the center as flux. Even though they offered a great variance in configurations, the number of pieces in Two x One and Twisted Grammar form families were harder to read.

Reflecting on this analysis, we iterated on the Twisted Grammar set with less flux and called this form family Bones (Figure 8, bottom left). This left us with the Bones shape family as a candidate for our form repertoire on this page.

Figurativeness analysis

Figurativeness is a tricky issue, given that humankind is good at drawing parallels between forms. An example is the phenomenon in which we 'see' faces in mundane objects like electrical sockets. To that end, forms that are abstract enough and that do not ring a specific bell were our goal. For example, we observed that the Snug form family resembled a fish or a bull figure, and the Thimble form family resembled the letter A or a rocket. Therefore, we eliminated these two forms from our repertoire of forms.

Figure 6. Figurativeness analysis.

Form diversity analysis

To achieve form diversity, we designed some shape families with different sizes or shapes. Sets with incremental size differences (i.e., Scales), we realized that configurations would be complicated. Children may try combining the wrong pieces, given that their observational and shape combination abilities are developing [25]. We realized that Oppose form family was more suited for this consideration. Additionally, the Bones shape family revealed earlier provides form diversity from the shape of the objects, making it suitable for this criterion.

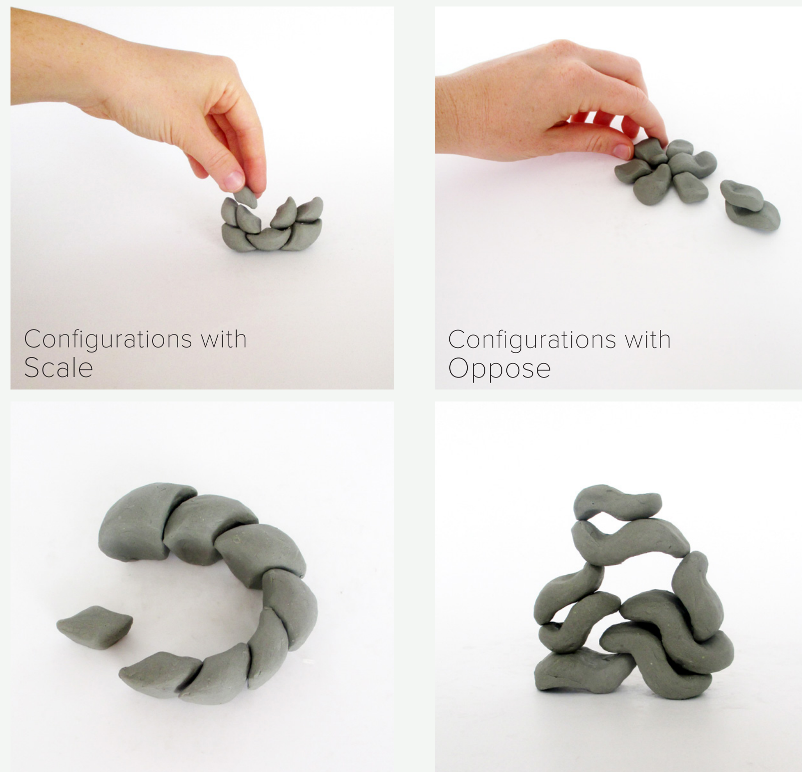


Figure 7. Diversity analysis.

CHILDREN ENGAGING WITH PHYSICAL OBJECTS

As we created and engaged with the forms, we narrowed down our form options based on the criteria we elicited earlier. However, this elimination process still left us with two object families: Bones and Oppose (Figure 8). At this crossroads, the designer could have chosen a form that she believed would suit the case study, envisioned usage scenarios, and integrated a specific technology. Most CCI research involves children as 'testers' of finished products and report technologies rather than providing insights applicable to the field[38,40]. With this awareness, we involved children in our early design process to further insights into their needs, skills, and preferences, empower them and inspire our TUI design.

OBSERVATIONAL STUDY

Young children's (under the age of 5) active involvement in the design processes is a developing practice. A recent review indicates that the number of research pursuing this approach is scarce, and only a few of them successfully included children in the design process [38]. Young children can become adrift from the design goal [20]or lose interest in the design process in co-design practices [28]. Observational methods are favored as they do not demand verbal articulation of ideas but reveal their behaviors that signal their opinions [5]. Using tangibles is favorable for bringing out children's needs from technology, and involving small groups or parents is suggested to help reveal deeper understanding [5,18].

Following these suggestions, we conducted an observational study with parent-child dyads. Our specific goals were exploring (i) which object family children preferred to play with to help us deduce the object to be used in the TUI setup, and (ii) forms of play that children came up with the objects to inspire TUI learning activities that capitalize on children's natural behavior. We also looked at how the objects influenced children's interactions and deduced how they might serve our overall research. The parents' involvement provided more insights into children's mindsets as they supported children's interactions on demand.

Selection and participation of children

Ethical approval for this study was obtained from the authors' university's Committee of Human Research. Thirteen parent-child dyads (Mage: 51 months, SD=4.71, gender distribution: 6F, 7M) were recruited from the author's university database. Parents received a document about the study. On top of being informed by their parents before the study, the researcher introduced herself, explained the study as 'understanding their insights and learn from how they play with novel objects,' and asked if they would like to participate. All children responded positively, and the parents signed the informed consent form. Furthermore, we stated that they could quit the session if they desired. Only one session was stopped halfway through as the child wanted to stop playing.

Setting and Procedure

Our study took place in various locations. Due to the Covid-19, we strove to conduct the outdoors (N=5), or in controlled spaces that provided distance and ventilation (N=4). Due to weather conditions and transportation difficulties, some studies were conducted at the dyad's homes (N=4). The setting differences are an unavoidable limitation. Yet, we believe that the studies conducted outside and at children's houses were more naturalistic than those conducted in the lab.

The procedure started with one object set presented to the children in randomized order. The children engaged with objects freely on their own first. The parents were asked not to intervene for the first five minutes to observe children's interpretations of the objects and play behaviors. Afterward, they were free to join to play session, which further diversified the interactions, revealed how they helped the children in their play endeavors. This process was repeated for both object sets and the procedure lasted around 25 minutes in total. After both objects' play sessions, the principal researcher asked the children which object set they preferred to play with and what else they wanted to do.

Throughout the procedure, the researcher sat quietly and took observation notes. All sessions were videotaped and transcribed. We analyzed the video based on our research inquiries, forms of play [31], and interaction differences based on the object set and behaviors that were not predicted by the research theme. Note that our goal was not to conduct a complete analysis of our data but to use these as inspiration informing the next steps in our research.

Materials

The Oppose and Bones objects were modeled via a CAD program and 3d-printed with non-toxic material. This production process was iterative to ensure that the physical arrangements were realized in balance and fit. We used the same color for both object sets to prevent children from making object preferences based on this. In each set, 18 objects were presented to the children.

Figure 8. Materials used in the study

FINDINGS

Children's object preferences

At the end of the study, we asked the children which set they preferred and their desired activities with them. We could not elicit responses from three participants. Two of them were reluctant to answer even though the parents asked in addition to the researcher. One participant left the study midway. For the rest of the participants, the result was a tie. Five of the participants preferred playing with Oppose; the other five wanted to play with Bones. All children's selection were motivated in their forms of play; they wanted to keep doing what they did with the objects. The duration of engagement with the sets revealed no significant differences. This impasse further validates the observational approach we followed, as children's behavior provided us with the design directions.

Forms of play

Children dominantly engaged in *pretend play* during their interaction period [31]. This entailed creating as-if scenarios with the objects. Children built narratives or shaped their interactions based on resemblances they found in configurations or single objects (Figure 9). We also observed *constructive play* more with the Bones object family, in which children tried building things with the objects. We reflect on this in the upcoming section on interactions specific to object forms. Further, we provide ***design takeaways (DT)*** that demonstrate how the observation may be used in a TUIs.

We assert that the forms were abstract and *open-ended* enough to reveal many scenarios [41]. Therefore, the TUI can accommodate these scenarios to keep children interested in the magnitude understanding setup. Yet, the variance in the scenarios with Oppose form family was less than the Bones form family. We believe this was caused by the Oppose objects' strong resemblance to seats and ducks from the children's perspective, as most narratives revolved around these. Though our design criteria and selection process did consider *non-figurativeness*, the interaction scenarios of children told another story.

Figure 9. Pretend play observations. DT: Design takeaways

Unanticipated interactions and object-based differences

We presented children with two different objects with different affordances. Affordance is an objects' apparent and definite features that suggest ways to use it [13]. We observed how these affordances affected children's interactions to help us shape our decision for the objects to be used in the TUI. We acknowledge that by nature, affordance is not solely embedded in the object but in many factors such as body and culture [13]. Also, stating that a specific form factor causes a specific behavior demand rigorous research with many participants, which is beyond our research scope. We, therefore, report our findings on a much humbler note and highlight some inspiring interactions that were unpredicted by the designer and how they may influence our upcoming work. Finally, based on our findings, we assert that the two form families bore different interactions.

Oppose form family

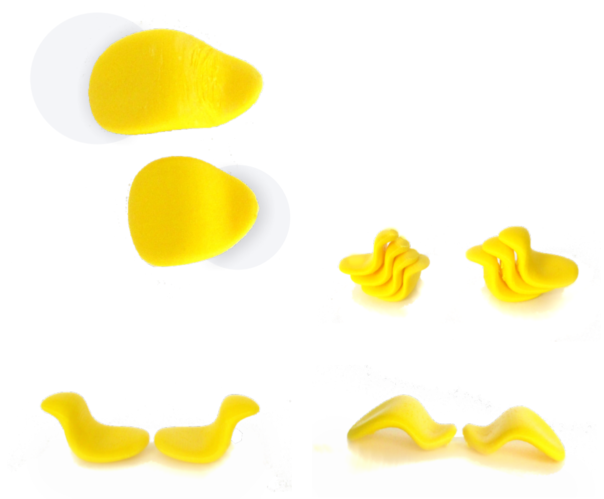


Figure 10. Oppose form family objects and arrangements.

A slower pace of interaction

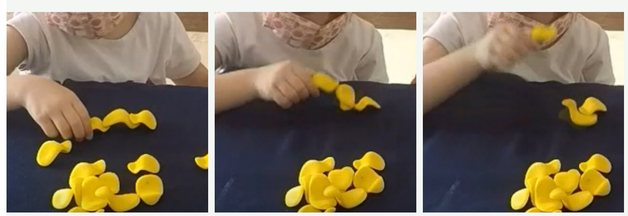
Children carefully handled the objects in Oppose family and played at a much slower pace than the Bones family. One of the drivers of this pace may be the challenge in handling the objects. The Oppose family objects have a thickness of 5 millimeters, relatively light and flimsy compared to the Bone form family. This difference seems to impact children's speed in construction.

Children expected their parent's help in realizing their constructions as handling the forms challenged them.

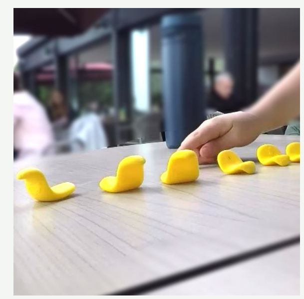
The parents provided guidance verbally and with gestures, or by physically helping them. In contrast, with the Bones family, the children did not demand support from their parents in realizing their construction goals.

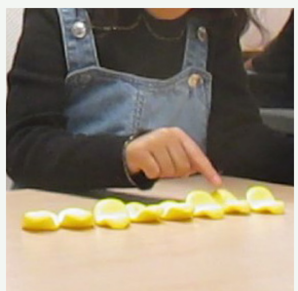
DT3 Challenging to handle forms may increase children's mindfulness in the interactions and slow their pace. Balancing activities may be also considered in this pursuit. These activities can be considered as a challenge for the dyads to take on.

Wobble, flip and giggles



Forms' partial contact to the surface created dynamic interactions. Oppose objects touch the ground on two small points on one side. Two participants used the tip of one Oppose object to flip others.





The form's rounded edge enabled them to rock back and forth. This wobbling was the highlight of children's interactions as they probed objects.

DT4 Consider the physical form features (e.g., wobbling forms) that afford dynamicity to increase engagement. For robust forms that do not have room for this, consider incorporating throwing or balancing activities to elicit excitement.

Figure 11. Children's interactions specific to Oppose objects.

Bones form family

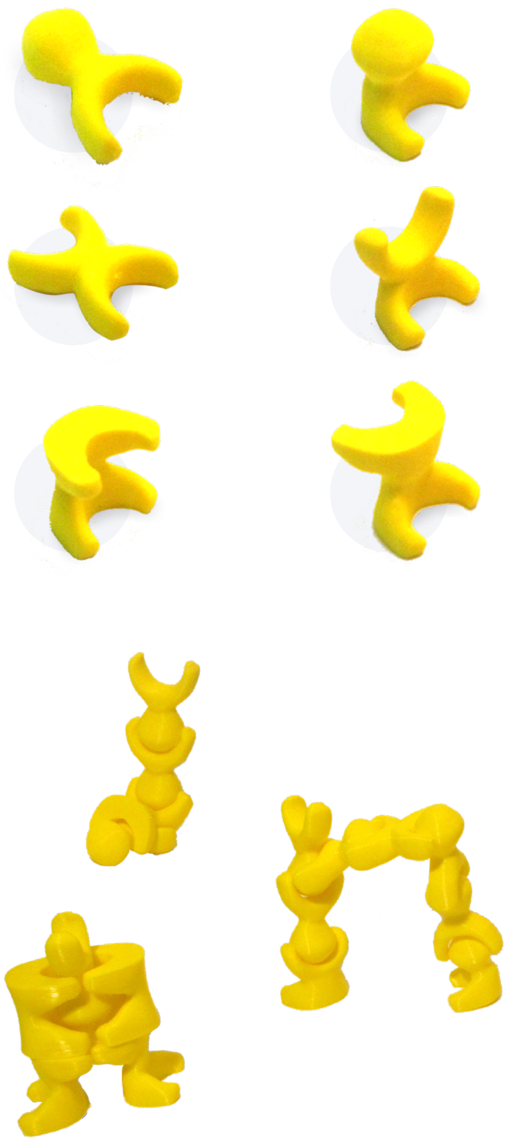


Figure 12. Bones form family objects and arrangements.

Constructions' trial and error

While some children created a myriad of configurations, this variance in arrangements was not realized by all. They did not know how to associate the knuckle-like connector pieces (Figure 10, top two pieces). Some parents revealed these pieces' potential in the construction (The two snapshots on the far right). This trial and error process was welcomed by some children who constantly experimented with the objects, which is a part of the natural learning process. Yet, some were quickly frustrated.

This trial and error process with the Bone family made us realize that what was apparent for adults was not always transparent for children. Our set was novel and unlike the popular construction kits. As observed, children can need support in realizing these possibilities, which the parent provided.

DT5 For tangibles that feature multiple forms, shape TUIs to help children find them (e.g., signal the objects with lights, vibrations). Highlight the potential object configurations (e.g., using light to show the contact points).

Objects as tools

One of the unexpected interactions we observed was using the Bone objects as tools to do other activities. The shapes within the family were used as a lens to look through. This was afforded by the crescent part of some objects and the ease of grabbing the connector pieces (Figure 10, top two pieces).

Some of the forms in the family were used to grab and lift objects. The form afforded it to be used as a 'crane' (in participant's terms).

DT6 Consider involving activities that use the objects as tools to introduce diversity in the usage scenarios of the TUI.

Figure 13. Children's interactions specific to Bones' objects.

REFLECTING ON THE STUDY

In the practice of research-though design, we often handle issues that appear trivial in the grand scheme of the research, which was the physical form of objects in our case. Yet, addressing the design of the physical object is a vital part of serving the overall goal of the research. In the observational study we explored (i) which object family children preferred to play with to help us deduce the object to be used in the TUI setup, and (ii) forms of play that children came up with the objects to inspire TUI learning activities that capitalize on children's natural behavior. We also reflected on the effect on forms in interactions and provided takeaways for future TUI studies.

Our first goal in the observational study was gauging the physical form children prefer. Children's answers revealed a tie. Therefore, we resolved to use the observations to help guide us. Having seen each form's unique contribution to the interaction, this is a tough call. We intend to choose the Bones family as it appears better suited to our magnitude understanding criteria. To explain, children built more varied configurations with the Bones family, which is one of our design criteria for magnitude understanding development. Further, even though we sought to minimize figurativeness in our designs per our design criteria, we realized that the Oppose form family was not so successful in this aspect.

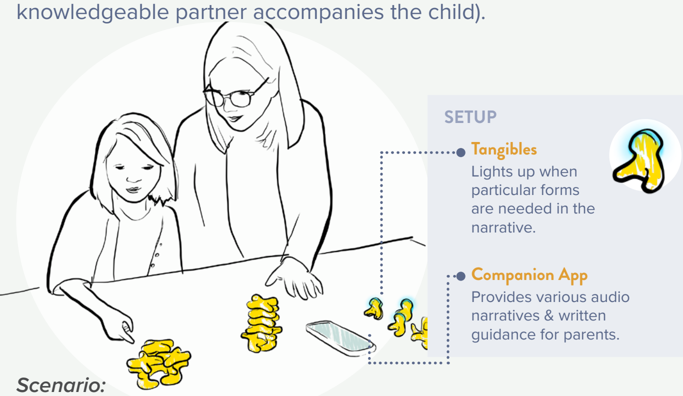
Our studies with children expanded our perspective to build a TUI, fulfilling our second goal. We gathered many *play narratives* from both objects (Figure 9). Children also approached some forms as *tools* that can help inspire other usage scenarios (Figure 13). The diversity in children's way of approaching objects was remarked by other work as well [13]. Research also reveals that an object's appearance may influence children's interactions more than the feedback provided [14,21,35]. We should highlight that our goal was not to deduce how many ways our objects could be used or ways to achieve desired actions in the TUI. Instead, we wanted to capitalize on the patterns we saw to inspire the learning activities and where technology may support interactions. An example of how the design takeaways meet magnitude understanding is shown in Figure 14.

In addition, our *design takeaways* (DT) can guide CCI researchers in ways to sustain engagement with TUIs. While ways to engage children in activities is a much-explored topic in research, we underline that considering engagement beyond the *novelty effect* remains a challenge. Many studies in CCI report new technologies or finished products that do not address the afterlife of these 'fun' tools [40]. Several ways can be explored to support a longer lifespan of the TUIs. A common method is providing responsive interactions and extrinsic motivation via feedback to prolong engagement [2,34]. On the other hand, intrinsic motivation can be sustained through *curiosity*. Fostering various interactions with the tangibles may break the monotony and spike children's curiosity [39]. For example, as one activity would focus on stacking, the other can feature flipping (DT 4), balancing challenges (DT 3) or carrying objects in different ways (DT 6) . Featuring activities that involve more bodily actions might help engage children who prefer more physically active activities (DT 2).

Our study provides initial insights into children's interactions with different objects. Future research can enlarge the sample to extend our findings. As a shortcoming of observational studies, the children's moods and the context may have affected our findings. To that end, the objects can be sent to homes like *probes* to arrive at more naturalistic outcomes [8,43]. The parents may document children's experiences with objects via photographs or in written form, and accounts from children can be extracted in the form of drawings.

TUI Design Concept Scenario: The Tree

The TUI provides guided play for dyads (i.e., a more knowledgeable partner accompanies the child).



Scenario:

1. The companion app offers several narratives to the dyads (Play scenarios, Figure 9). The child chooses *The Tree story*. The app starts emitting sounds of the forest and the dyads enact the audio narrative.

"Once there were two trees. One had two branches and the other has three branches" *[The necessary physical objects light up (Shown in drawing above) to help the child find them -> Design Takeaway 5] [The dyads place their 'branches' upon discussing which tree each would build.]*

2. *[The branches are placed, audio narrative continues]*

"The trees grew and had many leaves." *[Dyads place the leaf pieces that lit up on their branches and try to balance as much as possible -> Design Takeaway 3] [The app tells the knowledgeable partner to place less then the child in written form]*

3. "Three friends come to the field looking for a place to rest. They have to find the tree with more leaves."

[The dyads try to decide which tree to choose. The child chooses the tree that looks more in volume rather than focusing on the amount of units in the creations.] [The parent asks how she arrived at that decision and they dismantle to creation to be sure of their answer.]

4. *[The dyads place the friends that light up under the tree with more leaves.] [New narratives follow...]*

Figure 14. Scenario example with Bones shape family as a TUI

FUTURE STEPS

Our research is built on the idea that providing children with diverse cases of magnitudes can help them disentangle space and number [16,29]. On a critical note, our physical form-specific accounts may appear trivial when considering the overall goal of designing TUIs for magnitude understanding. A natural question is how exactly object designs affect magnitude understanding. We stress that objects alone do not promise learning in and of themselves [23]. The teaching context and the level of instructional guidance are some factors that influence the effectiveness of the designs in supporting learning [11,23]. To that end, our next steps will be forming a informed by our insights. Only then can we discuss our designs' effect on magnitude understanding.

To form the TUI, we will hold co-design workshops (i.e., with developmental psychologists, participants with experience in early childhood education, interaction designers) to arrive at age and subject-appropriate TUI design concepts. Our insights from the observational study will be of particular use at this stage. The participants will be presented with children's play (Figure 9) and usage scenarios (Figures 11, 13) with objects as design inspirations. We will discuss how magnitude understanding may be targeted in the activities (i.e., by incorporating a comparison of objects in different arrangements in play narratives) and design accordingly. The workshop will be concluded with a discussion about where the technology may support the design concepts. We will reflect on the design concepts and discussions to arrive at a final TUI design.

CONCLUDING REMARKS

This pictorial presented a glimpse into our *research-through design* (RtD) journey in designing TUIs for young children's magnitude understanding. Our journey starts with eliciting the physical *form criteria* for magnitude understanding from the literature. We then gathered inspiration from various resources on fulfilling the criteria and used sketches to capture our ideas. Next, we created physical prototypes and explored the interactions these forms offered from our perspective. Finally, we involved children's perspectives through an observational study with our objects. This helped us deduce *which forms* to choose, *inspired scenarios* we can adapt to the learning activities, and *interactions* we may play with to bring diversity into the TUI setup. Informed by the insights in our RtD journey, our next step will be designing a TUI through a *co-design* workshop.

Overall, our contribution to the CCI literature is three-fold: We provide (i) physical object designs for magnitude understanding, (ii) design takeaways for CCI researchers to be employed in TUI designs, and (iii) a n account of our RtD journey and the implications of a physical form-initiated research process.

Our design process yielded a diverse range of objects that can be employed in magnitude understanding research. We also highlighted the unanimity of forms used in math-TUI research. Note that our goal is not to refute established math practices (i.e., the use of traditional manipulatives) but to reconsider their boundaries. In most interdisciplinary research, while designers embody theory into practice, this curiosity might be lost. To remain critical about design decisions, careful consideration of what is taken for granted and where there is room for play could be explored [19].

We provided *design takeaways* for CCI researchers that may be applicable for TUI cases beyond magnitude understanding. To our knowledge, research has not specifically wondered about the effect of forms on interactions. How specific features of TUIs affect young children's learning remains a gap in CCI [36]. Our work acts as a step in exploring this with two distinct physical object sets. Instead of indexing how many ways our objects may be used, we approached what we saw as design inspirations (Figure 14).

Our pictorial partly responds to the need to demonstrate the complex processes involved in design [3,9,10,12]. We assert that our *physical form-initiated* TUI design process points at the need to consider and reflect on physical form of objects within TUIs. We observed that the differences amongst object forms created a variance in the interactions, some of which surpassed our expectations. Also, some of the physical *affordances* the designer intended were undiscovered as well. Since designers are the ones that generally design physical objects for young children, this urges us to be cautious about our assumptions in the designs. Physical form is one of the primary interfaces children encounter, which may even overshadow the intended uses directed by digital components of a TUI [21]. Overall, the influence of physical form factors within TUIs on young children may benefit from further exploration [36]. We assert that our design journey can inspire other researchers in developing TUIs for young children.

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