Modular Tangible User Interfaces: Impact of Module Shape and Bonding Strength on Interaction

Laura Pruszko, Hongri Gu, Julien Bourgeois, Yann Laurillau, Céline Coutrix

▶ **To cite this version:**

Laura Pruszko, Hongri Gu, Julien Bourgeois, Yann Laurillau, Céline Coutrix. Modular Tangible User Interfaces: Impact of Module Shape and Bonding Strength on Interaction. TEI '23: Proceedings of the Seventeenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '23), Feb 2023, Warsaw, Poland. 10.1145/3569009.3572731 . hal-03884342

HAL Id: hal-03884342
https://hal.science/hal-03884342

Submitted on 5 Dec 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Modular Tangible User Interfaces: Impact of Module Shape and Bonding Strength on Interaction

Laura Pruszko
Université Grenoble Alpes
Grenoble, France

Hongri Gu
Multi-Scale Robotics Lab, ETH Zurich
Zurich, Switzerland

Julien Bourgeois
Univ. Bourgogne Franche-Comté,
FEMTO-ST Institute, CNRS
Montbéliard, France

Yann Laurillau
Université Grenoble Alpes
Grenoble, France

Céline Coutrix
Université Grenoble Alpes, CNRS
Grenoble, France

ABSTRACT

Modular Tangible User Interfaces (TUIs) –i.e., UIs made of small-scale physical modules– offer novel opportunities for tangible interaction thanks to their highly customizable form factor. Such modular TUIs were proposed with different shape of modules and bonding strength between them. The problem we address in this paper is the lack of knowledge of how bonding strength and shape of the modules impact usability. We present the first study exploring the impact of bonding strength and module shape on subjective user ratings when interacting with a magnetic modular prototype. We assessed three levels of bonding strength (low, mid, high) and two shapes (cubes and rounded cubes) in a controlled user study. Participants performed eight common manipulations found in the literature for (non-)modular TUIs. Experimental results showed that (1) cubic modules are overall easier and more satisfying to manipulate, except for precision and bending tasks, (2) low strength impairs UI solidity, but high strength impairs precision tasks with cubic modules.

CCS CONCEPTS

• **Human-centered computing** → **Human computer interaction (HCI)**.

KEYWORDS

Tangible User Interfaces, Tangible interaction, Modular user interfaces, Bonding strength, Shape, Detachability, Solidity.

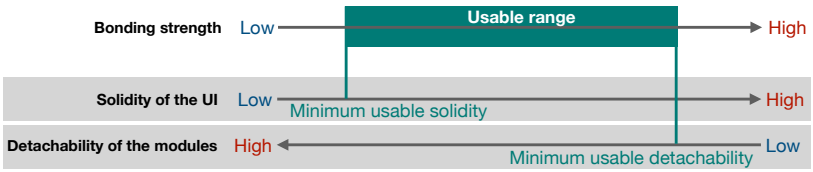
ACM Reference Format:
Laura Pruszko, Hongri Gu, Julien Bourgeois, Yann Laurillau, and Céline Coutrix. 2023. Modular Tangible User Interfaces: Impact of Module Shape and Bonding Strength on Interaction. In *TEI '23: Proceedings of the Seventeenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '23), February 26-March 1, 2023, Warsaw, Poland*. ACM, New York, NY, USA, 15 pages. https://doi.org/10.1145/3569009.3572731

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than ACM must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. Request permissions from permissions@acm.org.
TEI '23, February 26-March 1, 2023, Warsaw, Poland
© 2023 Association for Computing Machinery.
ACM ISBN 978-1-4503-9977-7/23/02…$15.00
https://doi.org/10.1145/3569009.3572731

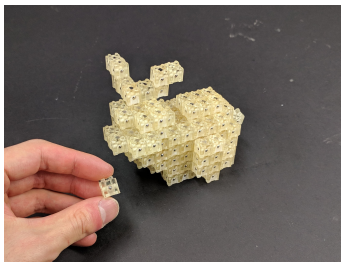
1 INTRODUCTION

Modular Tangible User Interfaces (TUIs) enable interaction through an ensemble of small scale physical elements –called modules– that the system *or* the user can rearrange to, e.g., adapt to the user, the task or the environment [10]. The novel benefit that such interfaces provide is their highly customizable form factor, enabling a wide range of possible shapes [38]. This opens new opportunities for tangible interaction. For example, Dynablock (Figure 1b) proposed dynamic 3D printing of user-reconfigurable objects composed of magnetic cubes [75]. PickCells [26] enabled physically reconfigurable touchscreens made of square screen cells that users can split to share with other users, change the shape of the device or create additional controls. chainFORM enabled reconfigurable displays, character animation and haptic interaction through modules assembled in a chain [50]. We currently lack knowledge on the trade-off between the detachability of the modules and the solidity of the overall modular UI (Figure 1a). On the one hand, if the modules stick strongly together they should form a robust modular UI, but may be more difficult to detach and reconfigure for the user. On the other hand, if the bonding strength between modules is low, they would be easier to detach and reconfigure for the user, but the overall modular UI might lack robustness.

In this paper, we seek to understand how this trade-off impacts user interaction with modular TUIs. We conduct the first study with passive magnets as bonding mechanism. Passive magnets –although not as strong as other alternatives, e.g., mechanical clamps [56] hinges [69], electromagnets [31, 53]– are simple to use, and allow the modules to self-align [66]. Magnets help users to reconfigure UIs made of small scale modules, both in 2D (e.g., [26, 45]) and in 3D (e.g., [66, 75]). Moreover, their low cost and small size factor enable scalable, cheap and highly reconfigurable modular UIs. For magnetic modules, we expect the detachability/solidity trade-off of the interface to depend on the holding force of the magnets themselves (that we call *"bonding strength"*), and on the shape of the modules. As with LEGO brick toys [29], we also expect the detachability/solidity trade-off to depend on the configuration of the modules: prior work mentioned that the denser the overall structure, the stronger it should be [62], but did not conduct a user study to measure this impact and inform future design. The problem we address in this paper is the lack of knowledge on the *usable range of bonding strength between magnetic modules* (Figure 1a) –i.e. the trade-off between detachability and solidity– as well as *how*



(a) The bonding strength should be low enough so users can detach the modules manually, while strong enough for the UI to hold its shape.



(b) Example of an object made of modules [75].

Figure 1: The expected trade-off between the detachability of the modules and the solidity of a modular TUI.

the shape of the modules and their configuration may further impact this trade-off.

Addressing this problem is important and timely (1) to inform current technological development, and (2) to avoid arbitrary and ad-hoc design choices in the future. The contributions in the field of modular TUIs are still at the design and prototype stages rather than interaction techniques and studies in the wild (e.g., [26, 45, 75]). Existing prototypes currently make use of ad-hoc shapes and strengths that are technology-driven and may not be optimized for users. The lack of user studies is a known challenge in the general field of shape-changing UIs. This is mainly explained by the fact that (1) isolating experimental factors and their effect is difficult with such UIs [10], and (2) the prototypes are often not robust enough to withstand prolonged user manipulation [10]. However, we expect that research on modular TUIs will advance in the upcoming years as the technology improves.

In order to overcome the challenges of conducting user studies with modular TUIs, we leverage recent work from robotics [30] to build simple passive magnetic modules of 6×6×6 mm^3. In a controlled user study, we gathered subjective ratings (*difficulty*, *satisfaction*, *impact of shape* and *impact of strength*) across eight types of tangible manipulations and two module configurations, performed with three levels of bonding strength –low (0.5mm-thick magnets of 0.49N), mid (1mm, 0.98N) and high (2mm, 2.45N)– and two module shapes (cubes and rounded cubes).

Experimental results not only confirms the existence of a detachability/solidity trade-off, but also measures the impact of module shape and bonding strength on the trade-off. Participants found cubic modules easier and more satisfying to manipulate, as they made for a robust UI even with low bonding strength. On the other hand, detaching one or two modules is easier and more satisfying with either rounded modules, as the gaps between rounded modules make them more prehensile, or cubic modules with lower strength (i.e., 0.5mm magnets). Bending the UI is easier with rounded modules with 1-2mm magnets, as rounded modules make the whole UI more flexible.

2 RELATED WORK

2.1 Manipulating modular TUIs

Previous work proposed a wide range of concepts and prototypes of modular UIs. We classify them according to how users manipulate them.

2 hands – 1 module interaction with large (decimeter) scale modules, e.g. TurkDeck [17] or Foxels [58].

1 hand – 1 module interaction with cm-scale modules that users can grasp one at a time, e.g. Siftables [46], Blinky Blocks [39] or Pickcells [26].

1 hand – *n* modules interaction with cm- to mm-scale modules that users can grasp together, e.g., GaussBricks [45], DynaBlock [75], or chainFORM [50].

We do not take into account swarm interfaces (e.g., Zooids [43], ShapeBots [76]) as they typically move independently and at a distance from each other and have little to no bonding. We also do not take into account shape displays (e.g., inFORM [21], Haptic Edge [35]) as they are constantly attached.

We particularly consider small modules enabling *1 hand - n modules* interaction. We study the smallest modules possible because research is currently trying to miniaturize modular TUIs (e.g., [10, 34, 43]). However, very few work has been conducted on modules under 1cm, especially 3D ones (see Figure 2 of [63]). HCI calls for miniature modules [10, 34, 43] to enable interaction with "stuff rather than things" [43] where the module is not the *interactive device* in itself, but the *material* used to create the UI. Radical Atom [34] states that the step between vision and technological implementation is to study users' needs. To open the way for research on small-scale modular TUIs and the novel interaction they could offer, we need to understand the user experience of manipulating such interfaces.

We particularly consider modules connected through magnets in order to easily prototype small modules. Passive magnets (e.g., [30, 45]) are the simplest among the docking mechanisms that seem to offer the most potential for miniaturization, with electrostatic actuators (e.g., [36, 48]), electromagnets (e.g., [24, 31]), and a combination of passive magnets with an additional actuation mechanism (e.g., pins [75], flywheel [66]). On the contrary, existing prototypes relying on mechanical docking mechanisms (e.g., hinges [50], clamps [56], hooks [82]), are difficult to miniaturize [10], which impairs their suitability for *1 hand - n modules interaction.*

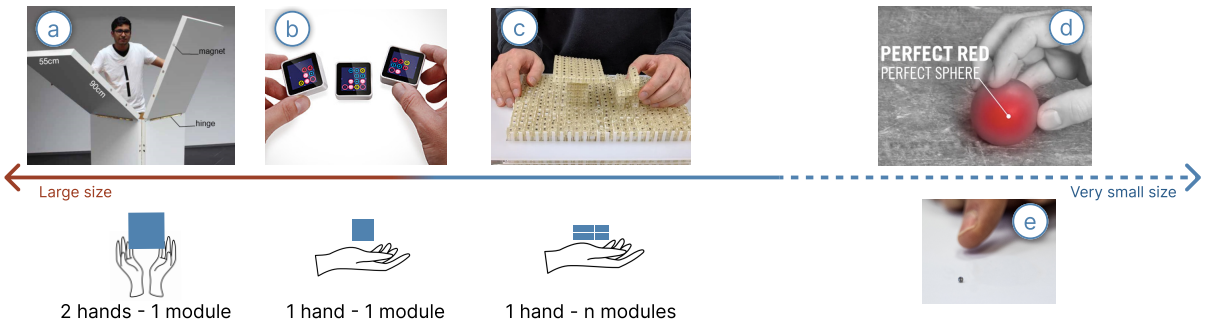


Figure 2: Modular TUIs enable a wide range of interaction modalities and prototypes, e.g. (a) reconfigurable smart VR environment [17], (b) reconfigurable touchscreens [46], or (c) dynamic 3D shape printings [75]. An example long-term vision for such interfaces is (d) Perfect Red [34], with modules as small as atoms, which could be achieved via modular solutions such as (e) the few mm Claytronics concept [59].

Previous work on modular TUIs proposed different interaction techniques and application scenarios. For example, Dynablock allows the user to programmatically "print" a shape and further refine it via direct manipulation [75] (see Figure 1b). PickCells enables physically reconfigurable touchscreens made of square screen cells that users can split to share with other users, change the shape of the device or create additional controls (e.g., a remote or a switch) [26]. GaussBricks proposed building blocks for tangible interaction on mobile touchscreens [45]. They leverage the elastic-like forcefeedback of magnetic forces to implement novel interactions, e.g. bending, pinching or stretching the modular TUI.

Previous work used ad-hoc bonding strength between modules and did not report their design rationale. Consequently, it is difficult for later designers to learn how to design tangible modules and their bonding strength from their experience. In order to enable the interaction techniques proposed in prior work, we study how the detachability/solidity trade-off impacts the different manipulations they proposed. We further describe these manipulations in section 3.3.

2.2 Magnetic actuation and bonding strength

Although we find a wide range of modular TUI prototypes and interaction modalities, to our knowledge previous work did not study the impact on user interaction of the bonding strength of the modules nor their shape. The lack of robustness of prototypes is a well-known issue in shape-changing interface research [10]. It reduces the opportunities to conduct controlled user studies and further understand the user experience of such interfaces [10].

In the HCI literature, we found magnetic implementations for other kinds of applications. For example, they can be implemented to provide haptic feedback (e.g., magnetic haptic patterns [84], force-feedback [85, 87]) or sense users' input in tangible controllers (e.g., [33, 85]). However, prior work do not provide insights on the impact of bonding strength in the context of modular TUIs.

In the robotics literature, modular robots have been studied since 1990 [23]. For instance, they propose magnetic modular implementations (e.g., [24, 30, 67]). They studied the technical strength trade-off: a docking mechanism between modules should aim at (1) maximizing the strength to achieve sufficient structure robustness while (2) minimizing the strength required to detach [18, 19]. However, they did not take a user-centered approach to evaluate this trade-off, nor their overall implementation design: the robotics community focuses on construction and locomotion rather than user interaction [69].

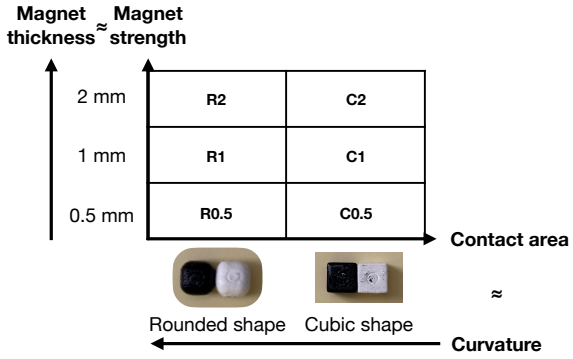
When searching for industry standards, we did not find studies nor guidelines on the detachability/solidity trade-off. We did find safety information related to the strength of magnets, especially on ingestion hazard. The U.S. Consumer Product Safety Commission advises that small magnets used in manipulated objects should have a flux index of 50 $kG^2.mm^2$ or less [1, 5]. The Toy Association states that strong magnets present a serious risk to children, and that safety standards prohibit the use of the powerful rare earth magnets in toys [2]. However, we did not find studies nor guidelines on the detachability/solidity trade-off. We believe that companies must have conducted such studies in the past, e.g. to design magnetic building block toys for children, but their results were not published. To fill this gap, we open this area of research by sharing all our study material together with our results.

3 METHOD

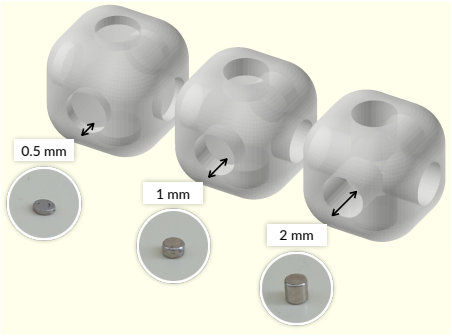
We conducted a controlled user study to investigate three levels of bonding strength between modules and two module shapes when manipulating a modular tangible prototype. We study their impact on eight manipulations from the literature with two different configurations of modules. Our goal is to understand how these design factors impact the trade-off between detachability of the modules and solidity of the prototype, by studying their impact on subjective user ratings when performing each manipulation with each condition.

3.1 Apparatus and participants

To study three levels of bonding strength (Figure 3a), we used three types of magnets varying in thickness: 0.5, 1 and 2mm thick magnets [4]. The resulting bonding strength of the modules depends on the thickness of the magnets they embed: the thicker, the stronger. The holding force on iron is 0.49N for the 0.5mm magnets, 0.98N for the 1mm magnets and 2.45N for the 2mm magnets.



(a) Independent variables from the experiments. We refer to them by a letter (Rounded: R, Cubic: C) × their magnet thickness. E.g., rounded modules × 2mm magnets are condition R2.



(b) Side by side comparison of the three magnet thicknesses used in this paper.

Figure 3: Independent variables of the prototypes studied in the paper: two *module shapes* (cubes and rounded cubes) × three *magnet thicknesses* (0.5mm, 1mm and 2mm) [4]. The thicker the magnets, the stronger their bonding strength.

To study module shape, we first review the shapes found in the literature. We find that current shapes range from cubes with sharp edges (e.g., [25, 69, 75]) via cubes with rounded edges [24, 26, 66], to quasi-spheres (e.g., [12, 52, 56, 72]). We left for future work shapes such as cylinders and triangles as they support 2D reconfiguration rather than 3D and/or allow for limited to no bonding between modules (e.g., [43, 44, 57, 57]).

To combine bonding strength and shape into a prototype, we first modeled our module as a cube in 3D. As research tends to miniaturize modules, we wanted to have the smallest module possible, while still being able to assess three different levels of bonding strength. The thinnest magnets available to the general public are 0.5mm. Thus, they serve as our weakest strength. The strongest magnets of the same diameter that can fit a cube smaller than DynaBlocks [75] are 2mm thick. We found that 0.2mm inner spacing between the magnets is the slimmest and strongest design. This results in an edge for the module $> 2 + 2 + 0.2 = 4.2$mm. Further increasing the thickness of the magnets results in the repelling forces at the center of the modules being too strong. Thus, 2mm thick magnets serve as our strongest strength. Lastly, we chose an intermediate thickness of 1mm.

We rounded the corners of the modules as much as possible without impairing the surface that would embed the magnets (Figure 3b): with magnets diameter being ⌀2 mm, the rounded corners of a 6×6×6 mm cube still allow for at least a ⌀2 mm flat surface when rounded (Figure 3). This allowed for the bonding strength due to magnets to be identical between cubic and rounded conditions.

For each condition, we 3D printed 80 modules using a Connex Stratasys Inkjet printer [3] (480 modules in total). We glued the magnets in each faces of the modules. Magnets induce the issue of geometric frustration: each features a south and a north pole, with only south-north able to bond together, and south-south or north-north repelling each others. To compose with this issue, each module has either all its faces south-facing or north-facing. We spray painted the south-facing modules black and the north-facing ones white for identification. Thanks to this, we can easily arrange the modules in a black and white checkerboard pattern as shown in Figure 4.

We recruited 12 participants from the local campus. Half self-identified as women and the other half as men (M = 28.33 y.o., SD = 10.2).

3.2 Experimental design

Our experiment followed a within-subject design with two independent variables (Figure 3):

Shape refers to the curvature of the edges of the cubes: either *cubic* (sharp edges) or *rounded*.

Bonding strength depends on the thickness of the magnets: 0.5 mm (0.49N holding force on iron), 1 mm (0.98N holding force on iron), and 2mm (2.45N holding force on iron).

We will refer to the combination of each condition by (1) a letter relating to its shape ('R' for rounded, 'C' for cubic) and (2) a number related to its strength (0.5, 1 or 2), e.g. rounded modules with 2mm magnets are condition 'R2'. The order of presentation of the conditions was counterbalanced through a latin square.

We collected four subjective dependant variables through a questionnaire: perceived difficulty (*"Overall, how difficult or easy did you find this task?"*), perceived satisfaction (*"Overall, how dissatisfying or satisfying did you find the task?"*), perceived impact of the strength (*"Overall, how did the strength impact the easiness/difficulty and satisfaction/dissatisfaction?"*), perceived impact of the shape (*"Overall, how did the edge type impact the easiness/difficulty and satisfaction/dissatisfaction?"*). We gathered additional qualitative subjective feedback with a semi-structured interview at the end of the experiment.

3.3 Experimental tasks

We reviewed the TUI literature to select the eight tasks our participants performed, presented as in Figure 4 from (a) to (h): split (a–d), lift (e), slide (f), fold (g) and bend (h). Based on our literature review, we considered the split task to be different depending on the number of manipulated modules: users may split one module (1), two modules (2), a line of modules (3) or half of the modules (4). We studied each of these four tasks separately.

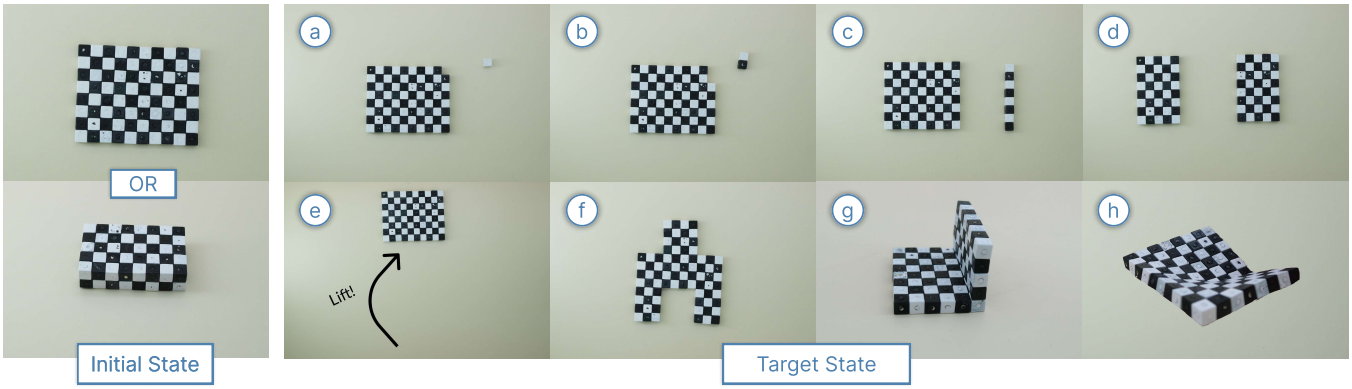


Figure 4: Participants performed manipulations on either a flat configuration, i.e. one layer of 80 modules (top left), or a thick configuration, i.e. two layers of 40 modules each (bottom left). From the prototype in its initial state shown in the left, participants performed eight manipulations (right): (a) split 1 module, (b) split 2 modules, (c) split a line of modules, (d) split the prototype in half, (e) lift, (f) slide, (g) fold and (h) bend.

First, TUIs report on widespread manipulations such as *translation* on a surface [43, 45, 76, 80], *rotation* on a surface [76, 79, 80], *lifting* from a surface [42, 54, 76]. However, during a pilot experiment, we found that varying the shape and bonding strength of the modules had little to no effect on translating and rotating tasks. For this reason, we only considered *lifting* in our experiment.

Second, non-modular shape-changing UIs enable specific manipulative tasks to support the change of shape. For example, they allow *bending* [13, 27, 28, 83], *folding* [64, 88], *stretching* [55, 83], *twisting* [13]. We found that, when applied to magnetic modular UIs *stretching* and *twisting* may lead to the same resulting shape: these lead to *splitting* the interface in the end. For this reason, we considered *bending*, *folding* and *splitting* for our experiment.

Third, modular UIs made of small elements enable specific manipulative tasks to support reconfiguration. From the references studied in our related work section, we found three main types of manipulations. Users can *split* the interface by separating one or multiple modules from the UI (e.g., [16, 26, 39, 45, 86]). Users can *bend* the interface, e.g., bend the whole surface (e.g., [45, 50, 51]), a corner [45, 68] or squeeze a ring [45]. Users can make parts of the interface *slide* against each other, e.g, to create handles to go from a rectangle shape to a game controller [26, 69], making a multi-parameter slider or dial [16]. For this reason, we considered *sliding* in our experiment in addition to *bending* and *splitting*.

Moreover, as previous work highlighted the impact of the thickness during tangible object manipulation [42], we want to test the manipulation on both flat and thick surfaces, i.e., a configuration with one or two layers of modules as shown in Figure 4 (left). Participants performed all eight tasks with the flat configuration and six tasks with the thick configuration: we found fold (Figure 4-g) and bend (Figure 4-h) too difficult in our pilot experiment. For instance, folding was not possible with thick prototypes –they directly split the prototype in two halves.

3.4 Procedure

After signing an informed consent form, the participant sits in front of a table with a delimited manipulation area. The experimental software presents the participants with a picture of a starting State A (e.g., a rectangular block) as shown in Figure 4 (left), and a target State B (e.g., the rectangular block split in two halves) as shown in Figure 4 (right). Reaching state B only requires the use of one elementary manipulation. There is no indication as to how the UI was grabbed to reach State B, to avoid biasing the manipulation. The experimenter places the first prototype on the manipulation area, mimicking State A. The participant manipulates the prototype to reach State B. The task is repeated three times to allow exploring different strategies. After completion of the task, the participant fills a short questionnaire. They are then presented with the next task to perform (i.e., new State A and B pictures) while the experimenter presents the next prototype. This procedure is repeated for each manipulation and each condition.

3.5 Data collection and analysis

We collected a total of 1008 data points for each question: 12 participants × 3 bonding strengths × 2 shapes × 14 tasks (6 with the thick configuration and 8 with the flat one).

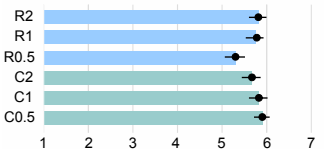
To analyze them, we rely on estimation techniques with 95% confidence intervals (CIs) as recommended by the APA [20] and which is becoming more and more a standard practice in HCI research (e.g., [11, 37, 41, 49, 71]). The effect size is computed between the scores of each questionnaire item for each condition, and refers to the difference between their geometric means. When interpreting the graphs, we conduct (1) an analysis of the means and confidence intervals across conditions and (2) pairwise analysis to identify the effect size between them. If the error bar (bootstrapped 95% CIs) does not overlap with 0, we consider that the difference between the two variables wields significance, the degree of which depending on the effect size. While we use estimation techniques, a p-value reading of our results is possible by comparing our CIs with common p-value spacing as shown in prior work [40].

4 RESULTS

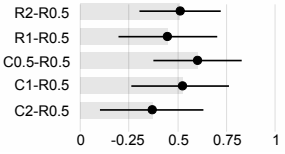
We now present our main results. We report the detailed mean score for each item in the questionnaire (i.e., difficulty, satisfaction, perceived impact of strength and perceived impact of shape) in Appendix A.

4.1 Overall results

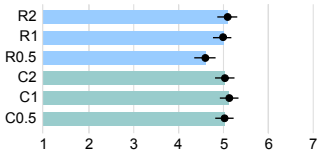
We first report the overall results across conditions, without discriminating between manipulation (i.e., the eight manipulations performed) nor configuration of the UI (i.e., flat with one layer of modules or thick with two layers of modules).



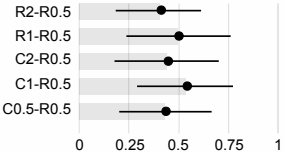
(a) Overall mean easiness for each condition. R0.5 was rated as the most difficult (5.3, CI [5.05,5.51]).



(b) Pairwise comparison to R0.5 (most difficult). C0.5 (easiest) was rated 0.6pt (CI [0.38, 0.83]) higher on the Likert scale than R0.5.



(c) Overall mean satisfaction between conditions. R0.5 was rated as the least satisfying (4.63, CI [4.38,4.85]).



(d) Pairwise comparison øR0.5 (least satisfying). C1 (most satisfying) was rated 0.54pt (CI [0.29, 0.77]) higher than R0.5.

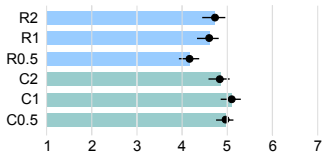
Figure 5: (Top) Easiness and (Bottom) satisfaction results for all manipulations and configurations aggregated. Error bars show bootstrapped 95% CIs. Figures on the left show the the geometric means. Figures on the right present the pairwise comparison between conditions to show the effect size. We find a significant difference between conditions if the error bar of the pairwise comparison does not overlap with 0.

4.1.1 Difficulty. Participants rated the tasks as slightly more difficult with the rounded modules (Easiness = 5.62/7 (1 = very difficult, 7 = very easy), CI [5.49,5.73]) compared to the cubic ones (5.8, CI [5.68,5.91]). Participants rated the tasks as slightly more difficult with the 0.5mm strength (5.6, CI [5.44,5.74]) compared to the 2mm strength (5.74, CI [5.59,5.88]). The tasks were overall more difficult with the R0.5 condition compared to all other conditions (Figures 5a and 5b).

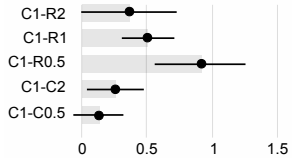
4.1.2 Satisfaction. We find evidence that participants rated the rounded modules (Satisfaction = 4.93/7 (1 = very dissatisfying, 7 = very satisfying), CI [4.79, 5.05]) to be overall slightly less satisfying compared to the cubic ones (5.1, CI [4.97, 5.21]). As shown in Figures 5c and 5d, the results show strong evidence that the participants rated the tasks to be overall less satisfying with the R0.5 condition compared to all other conditions. Overall, 0.5mm strength (4.84, CI [4.68, 5.0]) was rated as slightly less satisfying compared to 1mm (5.15, CI [4.99, 5.29]) and 2mm (5.05, CI [4.89, 5.21]).

4.1.3 Impact of the shape. For this item, we asked participants to rate how they perceived the impact of the shape on the completion of the task, from very negatively (1) to very positively (7). Overall, a cubic shape was perceived more positively (4.92, CI [4.79, 5.04]) compared to a rounded one (4.46, CI [4.31, 4.59]). As shown in Figures 6a and 6b, there is clear evidence that the R0.5 condition scored the lowest, and that C1 scored higher than C2, R2, R1 and R0.5.

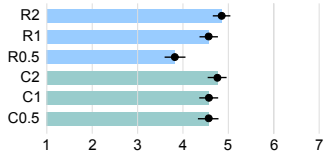
4.1.4 Impact of the strength. For this item, we asked participants to rate how they perceived the impact of the bonding strength on the completion of the task, from very negatively (1) to very positively (7). Overall, participants rated the 0.5mm strength (3.82, CI [3.59, 4.05]) as impacting the task negatively compared to both 1mm (4.57, CI [4.36, 4.76]) and 2mm (4.85, CI [4.65, 5.04]), while 2mm was rated slightly higher than 1mm. Figures 6c and 6d shows that there is a stronger impact of the strength on rounded modules. There is evidence that R0.5 was rated as having a more negative impact compared to R1 and R2. There is also smaller evidence that R2 scored higher than R1. We observe less variation for cubic modules, with only C2 rated marginally higher than C1 and C0.5.



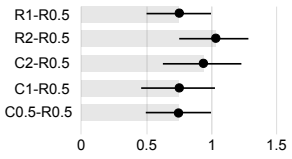
(a) Overall mean perceived impact of the shape. R0.5 shows the lowest impact of the shape (4.14, CI [3.9, 4.35]).



(b) Pairwise comparison to C1 (most positive). R0.5 (most negative) was rated 0.91pt (CI [0.55, 1.24]) lower than C1.



(c) Overall mean perceived impact of the strength. R0.5 shows the lowest impact of the strength (3.8, CI [3.59, 4.04]).



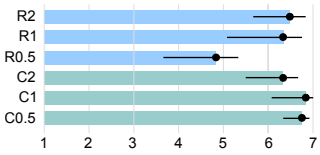
(d) Pairwise comparison to R0.5 (most negative). R2 (most positive) was rated 1.03pt (CI [0.74, 1.28]) higher than R0.5.

Figure 6: (Top) Perceived impact of the shape and (Bottom) of the strength results for all manipulations and configurations aggregated. Error bars show bootstrapped 95% CIs. Figures on the left show the the geometric means. Figures on the right present the pairwise comparison between conditions to show the effect size. We find a significant difference between conditions if the error bar of the pairwise comparison does not overlap with 0.

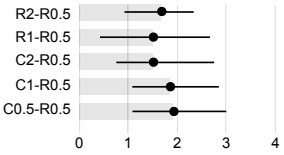
4.2 Results across manipulations and configurations

In the previous section, we discussed the overall results of the four items of the questionnaire. However, these results were aggregated across the eight manipulations (Figure 4, right) and configuration of the modules (Figure 4, left). This does not reflect the fact that participants rated the conditions differently depending on which manipulation they had to perform with them, and with which UI configuration (Figure 13). In this section, we refine our analysis by presenting the ratings separately for each manipulation and module configuration. In particular, we present the most important effect for each manipulation. To generate the other results and to reproduce these results, we include our data and analysis script in the supplementary material.

4.2.1 Lift. Overall, lifting was rated as the easiest task to perform with the thick configuration (6.9, CI [6.61,6.97]), but only second best with the flat configuration (6.27, CI [5.93, 6.51]). The reason is that, with a flat configuration, participants found the task to be harder with R0.5 (Figure 7). Indeed, we find strong evidence that (1) the cubic modules (5.01, CI [4.71, 5.31]) were perceived as having a more positive impact on the task compared to the rounded ones (4.1, CI [3.78, 4.40]) and that (2) for rounded modules, the stronger the better: the higher strength of R2 (4.96, CI [4.5, 5.42]) was perceived as having a more positive impact on the task compared to both R0.5 (3.71, CI [3.0, 4.38]) and R1 (4.42, CI [3.96, 4.92]). This is consistent with feedback from the interviews, e.g. P7 said about 0.5mm conditions that *"they are so weak that they deform and break just by lifting them."*.



(a) Mean easiness of the lift task between conditions. R0.5 (4.83, CI [3.67, 5.5]) was rated as the most difficult.



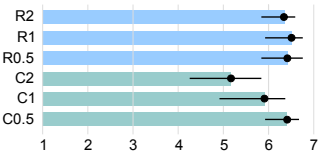
(b) Pairwise comparison to R0.5 (most difficult). C0.5 (the easiest) was rated 1.92pts (CI [1.08, 3.0]) easiest than R0.5.

Figure 7: Mean easiness of the lift task between conditions for the flat configuration. Error bars show bootstrapped 95% CIs. (Right) Pairwise comparisons show the effect size computed between means. We find significance between conditions if the error bar does not overlap with 0.

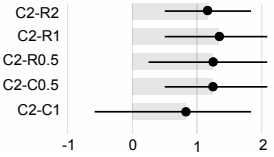
4.2.2 Split. Participants were asked to perform four kinds of splitting tasks, i.e. to either split 1 module, 2 modules, a line of modules or half of the prototype from the rest of the prototype.

Split 1 module. Overall, splitting one module from the prototype was rated as the easiest task with the flat configuration (6.52, CI [6.33, 6.66]). However, for the thick configuration (6.13, CI [5.83, 6.32]) (Figure 8a and 8b), we find that (1) the task was easier with rounded modules and (2) for cubic modules, the task was rated as slightly easier as the strength decreases, with C0.5 rated the easiest. On the other hand, we find evidence that C2 scored lower than any condition except C1. This is consistent with user feedback, e.g. P8 said that with C2 *"it's hard, I don't have fingernails, I can't grab it!"*.

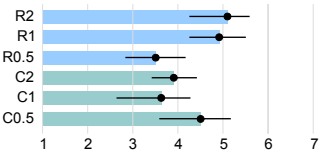
Split 2 modules. Overall, splitting two modules from the prototype was perceived as easier with the flat configuration (6.13, CI [5.92, 6.3]) compared to the thick configuration (5.3, CI [4.96, 5.56]). Especially, for the thick configuration, we find differences in how the strength was perceived across rounded and cubic modules (Figure 8c and 8d). We find evidence that 0.5 strength had a negative impact for rounded modules, with R0.5 (3.5, CI [2.83, 4.17]) scoring lower than R1 (4.92, CI [4.25, 5.5]) and R2 (5.08, CI [4.25, 5.58]), whereas 0.5 strength had a positive impact on cubic modules, with C0.5 (4.5, CI [3.58, 5.17]) scoring (marginally) higher than C1 (3.64, CI [2.64, 4.27]) and C2 (3.92, CI [3.42, 4.42]). As a result, although the task was perceived easier with rounded modules (5.64, CI [5.28, 5.92]) compared to cubic ones (4.94, CI [4.37, 5.37]), C0.5 was perceived easier compared to R0.5.



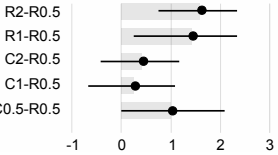
(a) Mean easiness of splitting 1 module. C2 (5.17, CI [4.25, 5.83]) was rated as most difficult than all except C1 ([5.9, CI 4.91, 6.36]



(b) Pairwise comparison to C2. R1 (easiest) was rated 1.33pts (CI [0.5, 2.08]) easier than C2.



(c) Mean perceived impact of the strength on splitting 2 module. R0.5 (3.5, CI [2.83, 4.17]) scored lower than all rounded conditions, but C0.5 (4.5, CI [3.58, 5.17]) scored higher than all cubic conditions.

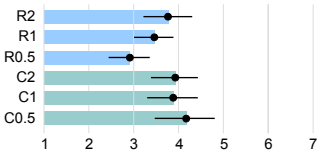


(d) Pairwise comparison to R0.5. R2 (highest) scored 1.58pts (CI [0.75, 2.33]) higher than R0.5

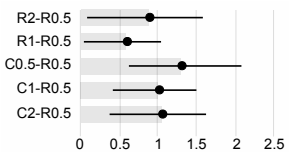
Figure 8: (Top) Mean easiness of splitting 1 module between conditions, for the thick configuration. (Bottom) Mean perceived impact of the strength on splitting 2 module between conditions, for the thick configuration. Error Bars show bootstrapped 95% CIs. (Right) Pairwise comparisons show the effect size computed between means. We find significance between conditions if the error bar does not overlap with 0.

Split a line of modules. Overall, splitting a line of modules from the prototype was rated as the most difficult task, both with the flat (4.71, CI [4.36, 5.01]) and thick configurations (4.41, CI [4.03, 4.76]). Still, there is evidence that the task was easier with cubic modules (4.93, CI [4.57, 5.24]) compared to the rounded ones (4.2, CI [3.85, 4.52]). Indeed, results show strong evidence that participants perceived a cubic shape as positively impacting the task (4.76,

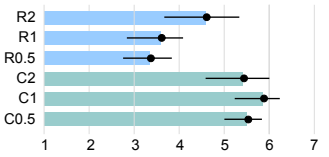
CI [4.42, 5.06]) compared to a rounded shape (3.51, CI [3.1, 3.9]). Moreover, results from Figures 9a and 9b show that, the lower the strength of rounded modules, the more negative the impact on the task, with R0.5 perceived more negatively than all other conditions. P5 commented *"ok that's less easy"* when performing the task with R1, and added *"wow this seems complicated"* when using R2. P5 felt that *"it's frustrating"* when using R2.



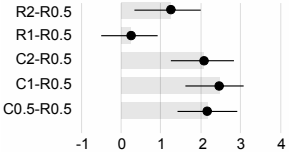
(a) Mean perceived impact of the strength on splitting a line of modules. R0.5 scored the lowest (2.91, CI [2.43, 3.35].



(b) Pairwise comparison to R0.5. C0.5 (highest) scored 1.29pts (CI [0.63, 2.08]) higher than R0.5.



(c) Mean perceived impact of the shape on splitting the UI in half. Lowering the strength worsen the impact of having a rounded shape, with R0.5 rated lowest (3.33, CI [2.75, 3.83]).

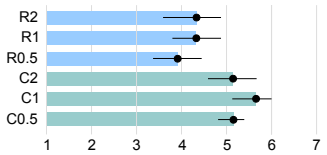


(d) Pairwise comparison to R0.5. C1 (highest) was rated 2.46pts (CI [1.62, 3.08]) higher than R0.5.

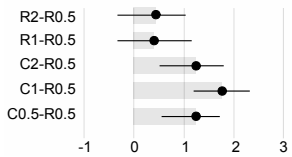
Figure 9: (Top) Mean perceived impact of the strength on splitting a line of modules between conditions for both configurations. (Bottom) Mean perceived impact of the shape on splitting the UI in half between conditions, for the flat configuration. Error Bars show bootstrapped 95% CIs. (Right) Pairwise comparisons show the effect size computed between means. We find significance between conditions if the error bar does not overlap with 0.

Split half of the modules. Results show that splitting the interface in two halves was perceived as easier with the thick configuration (6.38, CI [6.11, 6.55]) compared to the flat configuration (5.86, CI [5.52, 6.11]). In both cases, we observe that rounded modules and lower strength impair the interaction. Especially, for the flat configuration, we find strong evidence that (1) participants rated the shape of the cubic conditions (5.59, CI [5.22, 5.89]) as having a better impact on the task compared to rounded ones (3.83, CI [3.39, 4.25]) and that (2) the task was perceived as easier with cubic modules (6.19, CI [5.68, 6.46]) compared to rounded modules (5.52, CI [5.02, 5.89]). Moreover, we find evidence that decreasing the strength of rounded modules further worsen the perceived impact of the shape on the task for a flat configuration, as shown on Figures 9c and 9d. In addition, the higher the strength, the easier the task: R2 (6.08, CI [5.5, 6.5]) was easier than both R0.5 (5.17, CI [4.33, 5.75]) and R1 (5.33, CI [4.25, 6.0]). This is consistent with user feedback, e.g. P11 commented that *"the cubic ones are more suitable for detaching large blocks, it's easier to grab a big chunk"*, and further added that *"as for strength, when it's too weak it becomes a real pain when it comes to grabbing big chunks because you're breaking things you didn't want to break."*

4.2.3 Slide. Overall, the sliding task was easier with the thick configuration (5.66, CI [5.37, 5.88]) compared to the flat configuration (5.0, CI [4.68, 5.25]). P5 commented that *"ah yes it's easier with a layer underneath actually!"* As shown on Figure 10, we find strong evidence that the shape of cubic modules was perceived as having a more positive impact on sliding compared to rounded ones, with R0.5 scoring lowest and C1 scoring highest. Especially for the thick configuration, the task was rated as easier with (1) cubic modules (5.94, CI [5.53, 6.22]) compared to rounded ones (5.38, CI [4.97, 5.68]), and (2) with 1mm (6.04, CI [5.63, 6.33]) and 2mm strengths (5.79, CI [5.33, 6.12]) compared to 0.5mm (5.16, CI [4.6, 5.52]). Rounded modules with low strength were perceived as the most difficult (R0.5: 4.69, CI [3.85, 5.15]), while cubic modules with mid strength were the easiest (C1: 6.25, 5.5, 6.58). C1 was rated significantly higher than R0.5, C0.5 (5.67, CI [4.75, 6.08]) and R1 (5.83, CI [5.42, 6.17]). With both flat and thick configurations, we also find that R0.5 (4.2, CI [3.52, 4.72]) was rated as less satisfying than any condition except R2 (4.79, CI [4.13, 5.29]).



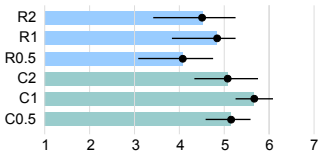
(a) Mean perceived impact of the shape on sliding parts of the UI. R0.5 scored lowest (4.69, CI [3.85, 5.12]) and C1 highest (6.25, CI [5.5, 6.7])



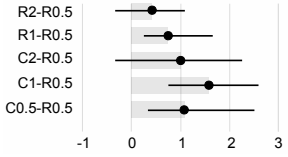
(b) Pairwise comparison to R0.5 (lowest). C1 (highest) scored 1.72pts (CI [1.2, 2.32]) higher than R0.5.

Figure 10: (Left) Mean perceived impact of the shape on sliding parts of the UI between conditions. Error Bars show bootstrapped 95% CIs. (Right) Pairwise comparisons show the effect size computed between means. We find significance between conditions if the error bar does not overlap with 0.

4.2.4 Fold. Participants only performed this task on a flat configuration, as folding was not possible with thick prototypes –they directly split the UI in two halves. Figures 11a and 11b show evidence that the shape of cubic modules had a more positive impact on the task compared to rounded ones. Overall, results show that participants mostly liked cubic modules with 1mm strength (C1), but disliked rounded modules with 0.5mm strength (R0.5):
(1) The task was more difficult with R0.5 (4.83, CI [3.58, 5.58]) compared to C1 (5.75, CI [4.83, 6.17]).
(2) The task was less satisfying with R0.5 (4.41, CI [3.33, 5.0]) compared to both C1 (5.5, CI [4.9, 5.83]) and R1 (5.17, CI [4.5, 5.59]).
(3) The impact of 0.5mm (3.75, CI [3.25, 4.21]) was perceived more negatively than both 1mm (4.83, CI [5.17, 4.33]) and 2mm (5.0, CI [4.37, 5.46]), with R0.5 (3.5, CI [2.83, 4.17]) scoring lower than both C1 (4.83, CI [4.25, 5.17]) and R1 (4.83, CI [4.0, 5.25]). P5 commented that *"in the end C1 is not bad for the things I couldn't do before"*.



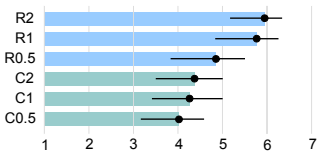
(a) Mean perceived impact of the shape on folding the UI. R0.5 was rated lowest (4.08, CI [3.08, 4.75]) and C1 highest (5.7, CI [5.25, 6.08]).



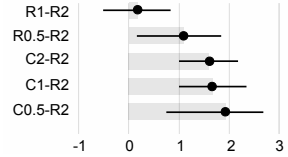
(b) Pairwise comparison to R0.5 (lowest). C1 (highest) was rated 1.58pts (CI [0.75, 2.58]) higher than R0.5.

Figure 11: (Left) Impact of the shape on folding the UI for both configurations. Results show that (1) the cubic shape (5.31, CI [4.94, 5.61]) had an overall better impact on folding the UI compared to rounded modules (4.47, CI [3.92, 4.89]). Error Bars show bootstrapped 95% CIs. (Right) Pairwise comparisons show the effect size computed between means. We find significance between conditions if the error bar does not overlap with 0.

4.2.5 Bend. Participants only performed this task on a flat configuration. Overall, participants preferred to bend the UI using rounded modules with 1-2mm strength, while they disliked cubic modules, especially with 0.5mm strength. Figures 12a and 12b show strong evidence that bending was more satisfying with the rounded modules compared to cubic ones, especially with 1-2mm strength: R1 and R2 were both more satisfying than all other conditions. Results also show that R2 (6.25, CI [5.5, 6.58]) was perceived as easier than all conditions except for R1 (5.83, 4.67, 6.42), which was rated as easier than both R0.5 (4.67, CI [3.42, 5.5]) and C0.5 (4.67, 3.75, 5.33). P12 commented that *"I see an advantage to rounded modules, especially for the bending task because it's impossible with cubes"*, and P7 added that *"I didn't know how to deform the squares without breaking them"*.



(a) Mean satisfaction on bending the UI. R1 (5.75, CI [4.83, 6.25]) and R2 (5.92, CI [5.17, 6.33]) were rated the highest.



(b) Pairwise comparison to R2 (highest). C0.5 (lowest) was rated as 1.91pts (CI [0.75, 2.67]) less satisfying than R2.

Figure 12: (Left) Mean satisfaction of bending the UI for both thick and flat configurations. Error Bars show bootstrapped 95% CIs. (Right) Pairwise comparisons show the effect size computed between means. We find significance between conditions if the error bar does not overlap with 0.

5 DISCUSSION

In this section, we discuss how the results of our user study can be readily used by HCI researchers working on modular TUIs, and how they can improve or extend them in the future.

5.1 Impact of module shape

Cubic modules have a more positive impact on the manipulation, and make the prototype easier and more satisfying to manipulate, except for bending and detaching one or two modules.

Detaching modules. The gaps in between rounded modules are found helping their prehensibility when the user needs to dislodge just one or two modules from the UI. For example, for detaching one/two rounded modules, P1 expressed that *"I just have to wedge my fingernails in between and they easily come apart"*, and for the cubic ones *"the corners dig into the fingertips, it's not comfortable"* but also that *"the cubes are easier detaching lines or splitting in two"*. P11 expressed that *"the cubic ones are more for detaching large blocks, it's easier to grab a big chunk, but when it comes to bending or recovering small pieces, then I'd rather have the rounded edges"*. On the one hand, rounded modules were especially disliked when the task required users to move a block of modules (i.e., split a line, split in half and slide). These manipulations required the participants to apply force on the top and bottom of the interface in a pinch grasp. A line or block of cubes, which do not have gaps between them, stay stiff and hold their shape, whereas rounded modules are more prone to falling off. On the other hand, the lack of gaps between cubic modules not only limits their prehensibility, but also increases the strength of the overall UI by granting it higher structural density. This benefits users when they need to detach blocks of modules.

Bending the UI. The gaps between rounded modules and their rounded edges give the interface a higher flexibility during bending tasks, whereas the straight edges of cubic modules make them split apart. Future design of modular TUIs should take the shape of the modules into account, as the elastic-like force feedback aspect of magnetic UIs was a major point in the design of GaussBricks [45]. Moreover, the HCI community takes a growing interest in tangible UIs allowing pressure-based interaction (e.g., [7, 22]). As current soft TUIs supporting pressure input do not allow yet for modularity, it would be interesting to test the limits of the flexibility of magnetic modular TUIs to propose an interface supporting both pressure, bending and modularity.

5.2 Impact of bonding strength

A mid to high bonding strength has a more positive impact on user manipulation, and makes the prototype easier and more satisfying to manipulate. For example, P1 expressed that *"When it's not strong enough, that's a disadvantage. Everything falls apart."*, while P8 expressed that *"I liked it better when the strength was stronger, [...] otherwise [the modules] go all over the place."* P12 added that, for the splitting or sliding tasks, *"when they are too weak [...] you have a 50% chance of having more modules coming off than what you intended"*.

However, the impact of the strength varies according to the manipulation users perform, to the shape of the modules, and to their configuration. For this reason, designers should carefully consider

the combination of these parameters to make sound decisions as follows.

Very weak magnets combined with rounded edges (R0.5) scored the lowest on all 4 items (difficulty, satisfaction, shape impact and strength impact), e.g. P6 *"the weakest strength with the rounded ones was when I complained most, it was coming off by itself"*. Moreover, when looking at the results for each manipulation, we find that R0.5 had a negative impact on all tasks except split 1 module, where it was more neutral. Even the lift manipulation, which was reportedly very easy, was more difficult with the R0.5 condition. P7 expressed that *"they are so weak that they deform and break just by lifting them"*. The combined effect of the low strength makes worst the previously discussed effect of the rounded shape. Lowering the strength weakens their solidity further and, according to experimental results, 0.5mm is already too low for rounded modules. In order to overcome this, designers can either (1) use stronger magnets, (2) sharpen the edges of the modules, or (3) use a denser configuration of modules to increase the overall solidity of the UI. However, very strong magnets combined with rounded edges and used for detaching one or two modules lead to negative results. P9 expressed that her/his preference went towards *"not too strong I would say. I found the R2 too strong and I couldn't manipulate them well."* P7 added that her/his preferred detaching the rounded modules because *"[they] are more grippy, especially since they have trouble coming off when the magnet is strong"*. Participants did not appear to have this same feedback on needing a strong, yet not-too-strong condition for the bending task.

Lowering the strength did not seem to negatively impact cubic modules as much as rounded modules. As expressed by P3, *"all cubic conditions, no matter how strong or weak the force is, I felt like it is quite stable."* P12 added that *"even with the weak magnets I can manipulate them better"*. However, experimental results show that the weakest strength (C0.5) impaired tasks where participants had to apply force on blocks (i.e., split half and slide) compared to stronger cubic modules. On the contrary, their lower strength proved to be an advantage when participants had to detach small parts. Splitting one or two modules was slightly easier with C0.5 compared to C1 and C2, and splitting a line was overall easier with C0.5 compared to all other conditions. As expressed by P10, *"for the strength it was more satisfying when you felt [the modules] were holding on, but it became more difficult to detach small parts."* As discussed in the previous section, the lack of gaps between cubic modules limits their prehensibility and increases the strength of the overall UI. We see that increasing their bonding strength further impairs users when they need to detach only one or two modules at a time, where C0.5 scored better than C1 and C2.

5.3 Implications for the design of future interaction techniques with modular TUIs

The modularity of TUIs uniquely enables interaction techniques such as splitting, e.g., one module [26, 46], and/or few modules at a time [31, 75]. Splitting allows reconfiguring the shape of the UI [70, 75] or sharing with another user [26, 46]. In our study, we find that cubic modules could be an issue for such interaction techniques. Rounding the corners of the modules, or providing users with some other kind of prehensile modality (e.g., textures or dents), would ease splitting. However, designers should carefully mind the impact on solidity. There could be benefits in trading higher detachability for lower solidity depending on the interaction context, e.g., if the modules are manipulated on a surface rather than held in the hand.

Most prior work on modular TUIs explored interaction techniques to be used on a table (e.g., [39, 46, 82, 89]). A few handheld interaction techniques were also proposed with Pickcells [26]. The solidity is critical if modules fall off in a handheld context compared to a tabletop one. Prior work tackled this issue by requiring modules to be constantly attached [69]. This extreme solution hinders the reconfigurability of the interface. To propose future interaction techniques with handheld modular TUIs, designers require both detachability and solidity. From our study, we find that a strength lower than that of our 0.5mm magnets (i.e., 0.49N holding force), especially with rounded modules, would not fit a handheld context. Results show that designers should either use higher bonding strength, or use alternatives to increase the solidity of the UI, such as sharper edges or denser/thicker configuration by stacking modules.

Prior work proposed interaction techniques leveraging the flexibility of the UI. Examples include bending the UI (e.g., [9, 73]), pressure-based input (e.g., [7, 22]) and providing elastic-like force feedback [45]. Our study shows that rounded modules are promising to implement such interaction techniques with modular TUIs. Future work on such techniques with modular TUIs should focus on solving the solidity drawback of rounded modules.

5.4 Implications for future technological development of modular TUIs

Our results will impact future technological development in both HCI and robotics. Current HCI implementations focus on cubic modules and need the user to be able to detach one, two or an ensemble of modules in their application scenarios [26, 46, 47, 70, 75]. Our study shows that the detachability/solidity trade-off is not a consistent one. Splitting one or two cubic modules was difficult as they are hardly prehensile. Detaching a line or a block of modules requires both high solidity for the modules to hold their shape, but also high detachability where the UI needs to split. To tackle this inconsistency, a perspective would be to use programmable bonding strength, possibly with electromagnetic or electrostatic actuators (e.g., [48, 67]). However, they are not readily available, more complex and less robust than passive magnets [67].

Another perspective is to explore shape-changing modules that can switch between sharp and rounded edges, as the gaps between rounded edges make the modules more prehensile and lowers the overall strength of the UI. Examples at a higher scale include the shape-changing hard disk that could change from a cube to a quasi-sphere [32]. However, making such shape-changing modules at the mm-scale is challenging. Future work could find opportunities in smart materials and soft robotics to dynamically change the shape of the modules. E.g., current advances in robotics explore deformable robotic modules using shape memory alloys that can switch between quasi-spheres and cubes by flattening their sides [60].

Another perspective for actuated, programmable modules could be their ability to self-reconfigure, e.g., programmatically change

their configuration in certain locations to increase or decrease the density of the UI structure, and thus its solidity. The system could help user re-configure the interface (e.g., driven by the modules [66, 69] or by external forces [24, 75]). The interface could also provide users with feed-forward indicating where and when the interface can be split. Current implementations in robotics focus on quasi-spherical modules to enable miniaturization, as a quasi-spherical design reduces the travel distance between contact points between modules [59]. There might be another trade-off between the strength needed for the modules to reconfigure, and the strength needed to hold their shape. Future work should investigate the benefits and drawbacks of this trade-off as soon as the technology allows it.

From our results, we see that a cubic design better supports users manipulation with mm-scale modules: the smaller the module, the smaller the magnets they can embed, and thus the weaker their bonding strength. The cubic modules did not suffer much from the lower strength, whereas our lowest strength already significantly impaired the rounded ones. Moreover, cubic modules have a wider contact area between them, and can thus embed larger – stronger – magnets. E.g., with our 6×6×6mm^3 prototypes we only used ⌀2mm magnets since the contact area between modules is only 2×2mm^2 for rounded modules. The available area for cubic modules, on the other hand, is 6×6mm^2. We expect that further rounding the edges would exacerbate our results: the rounder the module, the smaller the contact areas and the bigger the gaps. Thus, the higher the detachability and the lower the solidity of the interface. An avenue for future work could be to find an optimal module shape for this trade-off, e.g., cubes with a sharp edge but a dent, a notch or a surface texture that would improve detachability. Further alternatives are rounded polygons with more faces than a cube, thus allowing for more contact points between modules and stronger overall TUI, while allowing grasping their edges. Future work can leverage our results to improve splitting tasks with cubic modules to enable current application scenarios.

Prior work proposed modules larger than ours, at the cm-scale (e.g., [24, 39, 46, 67, 82], or the 9mm Dynablocks [75]). We believe that our results can apply to these cm-scale modules: on the one hand, increasing the size of the modules would enable a larger contact area and bigger –thus stronger– embedded magnets. We expect the additional weight of cm-scale modules to have limited impact on our results: for instance, with a 0.49N holding force on iron and a weight of 0.31g, two of our C0.5 modules need a pull force of 0.49N to detach. Using modules three times heavier (0.93g) would only increase the necessary pull force to 0.50N. With larger modules but with the same magnetic bonding strength, the number of contact points per unit volume (granularity [38]) is lower. This might decrease the solidity of the UI. Designers should then carefully choose a module configuration that compensate the lower number of contact points per volume (e.g., thicker configuration) [62] or increase the strength of the magnets. Although prior work in HCI proposed modules at the cm-scale, future work goes towards reducing the size of modules [34, 43] to enable a higher granularity, i.e. more modules per unit volume [38]. This paper aims at informing this future work.

5.5 Limitation of the study

While our study can already inform the design of modular TUIs and technological development, future work will extend and refine its results. As pointed out in prior work, isolating factors, such as the size, the weight or the arrangement of modules [62] that may have an impact on bonding strength is a grand challenge for research in modular TUIs [10]. While our study isolates the bonding strength and the shape in relation to the configuration of the interface, future work should study other related design parameters such as the size, the weight or other arrangements of modules. In order to allow for reproducibility and wider generalization of our results, we provide the STL files of our modules, our experimental data and the analysis script as supplementary materials.

Our experimental prototypes were not actuated. While the field of non-actuated modular TUIs (e.g., [26, 46, 47, 70, 75]) can already benefits from our results, we cannot be sure how our results will apply to future actuated modules. Research in actuated modules currently explore electromagnetic [31, 53] and electrostatic actuators [48, 59]. As the technology advances and the size of actuators decreases, future work should replicate this study to verify that our results apply to actuated modules.

We collected subjective ratings on easiness, satisfaction, and impact of strength and shape on the completion of the task. Subjective ratings are a major measure informing our knowledge on user experience with a prototype, especially with novel interaction paradigms [8, 61, 65]. Future work could extend our work further by gathering objective data, such as the users' time and effort to reconfigure the modular TUIs. First, we did not measure the time to complete the tasks in our study as we left the participants free to explore different manipulations. This made any time comparison difficult. Future work should leverage our qualitative data on how the participants manipulated the prototypes to select the best manipulation strategies and compare completion time. The videos we collected [6] are available on Zenodo. Second, the effort could be measured through the force applied by participants on the prototypes. Candidates technologies are, e.g., electromyography (EMG). The use of surface EMG to study gesture-based interactions is common in HCI [15, 77, 78]. EMG measures muscle activity but is not reliable to measure the actual force users apply on a surface [14]. E.g., the muscle of the thumb can show high activity when the user contracts it without actually applying force on the prototype. The effort could alternatively be measured by a glove worn by the participant [81]. Unfortunately, using gloves impairs grip force [74]. Future work should consider using other alternatives such as using sensors embedded in or on the prototype [22]. Subsequent work is needed to embed sensors in our prototype: embedding sensors between the modules is not straightforward as it would lower their bonding strength.

Lastly, our participants were all adults with no motor skills impairment. Future applications of modular TUIs could benefit all kinds of public, e.g., children and elderly users. In order to open up the design of magnetic modular TUIs for a wider range of users, future studies on the detachability/solidity trade-off could be conducted with participants presenting different motor skills. In addition, with future modules as such mm-scale, further work is needed to ensure children's safety and avoid any ingestion hazard.

6 CONCLUSION

Modular TUIs enable new interaction techniques through their highly customizable form-factor. Magnetic modular TUIs offer great opportunities in terms of costs, scalability and miniaturization. In this paper, we conducted the first user study on how the shape and bonding strength of such modules impact common manipulations from HCI literature. We provide the first study of the trade-off between the detachability of the modules and the solidity of the UI. As expected, the higher the bonding strength, the higher the solidity but the lower the detachability. But, although we initially aimed at finding a single usable range (Figure 1), we found that the range of suitable bonding strength and shape depends on the manipulation. We show that cubic $6 \times 6 \times 6$ mm^3 plastic modules with magnets of 0.98N-2.45N holding strength on iron provide optimal easiness and satisfaction when manipulating large blocks of modules and for folding and lifting the prototype, while 0.49N holding force impaired these tasks. Rounded $6 \times 6 \times 6$ mm^3 plastic modules with 2.45N holding strength on iron provide optimal easiness and satisfaction for precise detachment of 1 or 2 modules at a time and for bending tasks, while 0.49N holding strength significantly impairs these tasks. Changing the configuration of the modules, e.g., the thickness of the TUI, is a way of increasing/decreasing the solidity. For example, although rounded modules with 0.49N holding strength impaired the lifting task on a flat configuration, there was no similar decrease in satisfaction nor easiness when using a thicker configuration with two layers of modules instead of one.

The HCI community can readily leverage this work to inform the design of interaction techniques and technological implementation. We expect future work on programmable bonding strength and self-reconfigurable actuated modules to overcome the challenge for detaching several modules, requiring both high solidity and high detachability.

ACKNOWLEDGMENTS

This work was supported by the French National Research Agency (ANR-21-CE33-0009) and the LabEx PERSYVAL-Lab (ANR-11-LABX-0025-01) funded by the French program Investissement d'avenir. We are grateful for the feedback we received from colleagues and reviewers.

REFERENCES

[1] 2020. Magnet Sets - ASTM F3458-21. https://www.cpsc.gov/Regulations-Laws--Standards/Voluntary-Standards/Topics/Magnet-Sets.

[2] 2020. The Toy Association Statement on Magnets in Toys. https://www.toyassociation.org/PressRoom2/IndustryStatements/ToySafety/statement-on-magnets.aspx.

[3] 2022. Connex3 Objet500 and Objet350. https://www.stratasys.com/3d-printers/objet-350-500-connex3.

[4] 2022. HKCM Engineering e.K. professional magnet supplier. https://www.hkcm.de/.

[5] 2022. Safety Standard for Magnets. https://www.federalregister.gov/documents/2022/01/10/2021-27826/safety-standard-for-magnets.

[6] 2022. Video recordings of "Modular Tangible User Interfaces: Impact of Module Shape and Bonding Strength on Interaction". https://doi.org/10.5281/zenodo.7372398.

[7] Alexander T. Adams, Elizabeth L. Murnane, Phil Adams, Michael Elfenbein, Pamara F. Chang, Shruti Sannon, Geri Gay, and Tanzeem Choudhury. 2018. Keppi: A Tangible User Interface for Self-Reporting Pain. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*. ACM Press, Montreal QC, Canada, 1–13. https://doi.org/10.1145/3173574.3174076

[8] David Ahlström, Khalad Hasan, and Pourang Irani. 2014. Are you comfortable doing that?: acceptance studies of around-device gestures in and for public settings. In *Proceedings of the 16th international conference on Human-computer interaction with mobile devices & services - MobileHCI '14*. ACM Press, Toronto, ON, Canada, 193–202. https://doi.org/10.1145/2628363.2628381

[9] Teemu T. Ahmaniemi, Johan Kildal, and Merja Haveri. 2014. What is a device bend gesture really good for?. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Toronto Ontario Canada, 2014-04-26). ACM, 3503–3512. https://doi.org/10.1145/2556288.2557306

[10] Jason Alexander, Anne Roudaut, Jürgen Steimle, Kasper Hornbæk, Miguel Bruns Alonso, Sean Follmer, and Timothy Merritt. 2018. Grand Challenges in Shape-Changing Interface Research. In *the CHI 2018 Conference*. New York, New York, USA, 1–14. https://doi.org/10.1145/3173574.3173873

[11] Lonni Besançon, Mehdi Ammi, and Tobias Isenberg. 2017. Pressure-Based Gain Factor Control for Mobile 3D Interaction using Locally-Coupled Devices. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver Colorado USA, 2017-05-02). ACM, 1831–1842. https://doi.org/10.1145/3025453.3025890

[12] Julien Bourgeois, Benoît Piranda, André Naz, Nicolas Boillot, Hakim Mabed, Dominique Dhoutaut, Thadeu Tucci, and Hicham Lakhlef. 2016. Programmable matter as a cyber-physical conjugation. *SMC* (2016). https://dblp.org/rec/conf/smc/BourgeoisPNBMDT16

[13] Eric Brockmeyer, Ivan Poupyrev, and Scott Hudson. 2013. PAPILLON: designing curved display surfaces with printed optics. In *Proceedings of the 26th annual ACM symposium on User interface software and technology*. ACM, St. Andrews Scotland, United Kingdom, 457–462. https://doi.org/10.1145/2501988.2502027

[14] T.W. Calvert and A.E. Chapman. 1977. The relationship between the surface EMG and force transients in muscle: Simulation and experimental studies. 65, 5 (1977), 682–689. https://doi.org/10.1109/PROC.1977.10547

[15] Baptiste Caramiaux, Marco Donnarumma, and Atau Tanaka. 2015. Understanding Gesture Expressivity through Muscle Sensing. *ACM Transactions on Computer-Human Interaction* 21, 6 (Jan. 2015), 31:1–31:26. https://doi.org/10.1145/2687922 Number: 6.

[16] Liwei Chan, Stefanie Müller, Anne Roudaut, and Patrick Baudisch. 2012. CapStones and ZebraWidgets: sensing stacks of building blocks, dials and sliders on capacitive touch screens. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, Austin Texas USA, 2189–2192. https://doi.org/10.1145/2207676.2208371

[17] Lung-Pan Cheng, Thijs Roumen, Hannes Rantzsch, Sven Köhler, Patrick Schmidt, Robert Kovacs, Johannes Jasper, Jonas Kemper, and Patrick Baudisch. 2015. TurkDeck: Physical Virtual Reality Based on People. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology* (Charlotte NC USA, 2015-11-05). ACM, 417–426. https://doi.org/10.1145/2807442.2807463

[18] Jay Davey, Ngai Kwok, and Mark Yim. 2012. Emulating self-reconfigurable robots - design of the SMORES system. In *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, Vilamoura-Algarve, Portugal, 4464–4469. https://doi.org/10.1109/IROS.2012.6385845

[19] Jay Davey, Jimmy Sastra, Matt Piccoli, and Mark Yim. 2012. ModLock: A manual connector for reconfigurable modular robots. In *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*. 3217–3222. https://doi.org/10.1109/IROS.2012.6386190 ISSN: 2153-0866.

[20] Gary R. VandenBos (Ed.). 2009. *Publication Manual of the American Psychological Association (6th ed.)*. http://www.apastyle.org/manual/

[21] Sean Follmer, Daniel Leithinger, Alex Olwal, Akimitsu Hogge, and Hiroshi Ishii. 2013. inFORM: dynamic physical affordances and constraints through shape and object actuation. In *UIST '13: Proceedings of the 26th annual ACM symposium on User interface software and technology*. ACM, New York, New York, USA, 417–426. https://doi.org/10.1145/2501988.2502032

[22] Bruno Fruchard. 2021. Squish This: Force Input on Soft Surfacesfor Visual Targeting Tasks. (2021), 9.

[23] Toshio Fukuda' and Yoshio Kawauchi. 1990. Cellular Robotic System(CEB0T) as One of the Realization of Self-organizing Intelligent Universal Manipulator. 6.

[24] Kyle Gilpin, Ara Knaian, and Daniela Rus. 2010. Robot pebbles: One centimeter modules for programmable matter through self-disassembly. In *2010 IEEE International Conference on Robotics and Automation*. IEEE, Anchorage, AK, 2485–2492. https://doi.org/10.1109/ROBOT.2010.5509817

[25] Kyle Gilpin, Keith Kotay, Daniela Rus, and Iuliu Vasilescu. 2008. Miche: Modular Shape Formation by Self-Disassembly. *The International Journal of Robotics Research* 27, 3-4 (March 2008), 345–372. https://doi.org/10.1177/0278364907085557 Number: 3-4.

[26] Alix Goguey, Timothy Neate, Jennifer Pearson, Simon Robinson, Matt Jones, Cameron Steer, Andrés Lucero, Laurence Nigay, Deepak Ranjan Sahoo, Céline Coutrix, Anne Roudaut, Sriram Subramanian, and Yutaka Tokuda. 2019. PickCells: A Physically Reconfigurable Cell-composed Touchscreen. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI '19*. ACM Press, Glasgow, Scotland Uk, 1–14. https://doi.org/10.1145/3290605.3300503

[27] Antonio Gomes, Andrea Nesbitt, and Roel Vertegaal. 2013. MorePhone: a study of actuated shape deformations for flexible thin-film smartphone notifications. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, Paris France, 583–592. https://doi.org/10.1145/2470654.2470737

[28] Antonio Gomes, Lahiru Lakmal Priyadarshana, Aaron Visser, Juan Pablo Carrascal, and Roel Vertegaal. 2018. Magicscroll: a rollable display device with flexible screen real estate and gestural input. In *Proceedings of the 20th International Conference on Human-Computer Interaction with Mobile Devices and Services*. ACM, Barcelona Spain, 1–11. https://doi.org/10.1145/3229434.3229442

[29] The LEGO group. 2021. https://www.lego.com/en-us/lego-history/the-stud-and-tube-principle-001aa762568348239d659d4ffdc2dfe3

[30] Hongri Gu, Quentin Boehler, Daniel Ahmed, and Bradley J. Nelson. 2019. Magnetic quadrupole assemblies with arbitrary shapes and magnetizations. *Science Robotics* 4, 35 (Oct. 2019), eaax8977. https://doi.org/10.1126/scirobotics.aax8977

[31] Simon Hauser, Mehmet Mutlu, and Auke J. Ijspeert. 2020. Kubits: Solid-State Self-Reconfiguration With Programmable Magnets. 5, 4 (2020), 6443–6450. https://doi.org/10.1109/LRA.2020.3013884

[32] Oren Horev. 2006. *Talking to the hand: An exploration into shape shifting objects and morphing interfaces*. Master's thesis. Interaction Design Institute Ivrea.

[33] Sungjae Hwang, Myungwook Ahn, and Kwang-yun Wohn. 2013. MagGetz: customizable passive tangible controllers on and around conventional mobile devices. In *Proceedings of the 26th annual ACM symposium on User interface software and technology*. ACM, St. Andrews Scotland, United Kingdom, 411–416. https://doi.org/10.1145/2501988.2501991

[34] Hiroshi Ishii, Dávid Lakatos, Leonardo Bonanni, and Jean-Baptiste Labrune. 2012. Radical atoms: beyond tangible bits, toward transformable materials. *Interactions* 19, 1 (Jan. 2012), 38–51. https://doi.org/10.1145/2065327.2065337

[35] Sungjune Jang, Lawrence H. Kim, Kesler Tanner, Hiroshi Ishii, and Sean Follmer. 2016. Haptic Edge Display for Mobile Tactile Interaction. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. Association for Computing Machinery, New York, NY, USA, 3706–3716. https://doi.org/10.1145/2858036.2858264

[36] M. E. Karagozler, J. D. Campbell, G. K. Fedder, S. C. Goldstein, M. P. Weller, and B. W. Yoon. 2007. Electrostatic latching for inter-module adhesion, power transfer, and communication in modular robots. In *2007 IEEE/RSJ International Conference on Intelligent Robots and Systems*. 2779–2786. https://doi.org/10.1109/IROS.2007.4399492 ISSN: 2153-0866.

[37] Elio Keddisseh, Marcos Serrano, and Emmanuel Dubois. 2021. KeyTch: Combining the Keyboard with a Touchscreen for Rapid Command Selection on Toolbars. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama Japan, 2021-05-06). ACM, 1–13. https://doi.org/10.1145/3411764.3445288

[38] Hyunyoung Kim, Celine Coutrix, and Anne Roudaut. 2018. Morphees+: Studying Everyday Reconfigurable Objects for the Design and Taxonomy of Reconfigurable UIs. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*. ACM Press, Montreal QC, Canada, 1–14. https://doi.org/10.1145/3173574.3174193

[39] Brian T. Kirby, Michael Ashley-Rollman, and Seth Copen Goldstein. 2011. Blinky blocks: a physical ensemble programming platform. In *Proceedings of the 2011 annual conference extended abstracts on Human factors in computing systems - CHI EA '11*. ACM Press, Vancouver, BC, Canada, 1111. https://doi.org/10.1145/1979742.1979712

[40] Martin Krzywinski and Naomi Altman. 2013. Error bars. 10, 10 (2013), 921–922. https://doi.org/10.1038/nmeth.2659

[41] Caitlin Kuhlman, Diana Doherty, Malika Nurbekova, Goutham Deva, Zarni Phyo, Paul-Henry Schoenhagen, MaryAnn VanValkenburg, Elke Rundensteiner, and Lane Harrison. 2019. Evaluating Preference Collection Methods for Interactive Ranking Analytics. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow Scotland Uk, 2019-05-02). ACM, 1–11. https://doi.org/10.1145/3290605.3300742

[42] Mathieu Le Goc, Pierre Dragicevic, Samuel Huron, Jeremy Boy, and Jean-Daniel Fekete. 2016. A Better Grasp on Pictures Under Glass: Comparing Touch and Tangible Object Manipulation using Physical Proxies. In *Proceedings of the International Working Conference on Advanced Visual Interfaces*. ACM, Bari Italy, 76–83. https://doi.org/10.1145/2909132.2909247

[43] Mathieu Le Goc, Lawrence H Kim, Ali Parsaei, Jean-Daniel Fekete, Pierre Dragicevic, and Sean Follmer. 2016. Zooids: Building Blocks for Swarm User Interfaces. In *UIST'16*. 1–13. https://doi.org/10.1145/2984511.2984547

[44] Yujin Lee, Myeongseong Kim, and Hyunjung Kim. 2020. Rolling Pixels: Robotic Steinmetz Solids for Creating Physical Animations. In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction* (New York, NY, USA, 2020-02-09) *(TEI '20)*. Association for Computing Machinery, 557–564. https://doi.org/10.1145/3374920.3374987

[45] Rong-Hao Liang. 2014. GaussBricks: Magnetic Building Blocks for Constructive Tangible Interactions on Portable Displays. (2014), 9.

[46] David Merrill, Jeevan Kalanithi, and Pattie Maes. 2007. Siftables: towards sensor network user interfaces. In *Proceedings of the 1st international conference on Tangible and embedded interaction - TEI '07*. ACM Press, Baton Rouge, Louisiana, 75. https://doi.org/10.1145/1226969.1226984

[47] David Merrill, Emily Sun, and Jeevan Kalanithi. 2012. Sifteo Cubes. In *CHI '12 Extended Abstracts on Human Factors in Computing Systems* (Austin, Texas, USA) *(CHI EA '12)*. Association for Computing Machinery, New York, NY, USA, 1015–1018. https://doi.org/10.1145/2212776.2212374

[48] Kei Misumi, Gwenn Ulliac, Naoto Usami, Benoit Piranda, Yoshio Mita, Akio Higo, and Julien Bourgeois. 2020. Micro-scale Electrostatic Attach-detach Device for Self-reconfigurable Modular Robotic System. In *2020 Symposium on Design, Test, Integration Packaging of MEMS and MOEMS (DTIP)*. 1–4. https://doi.org/10.1109/DTIP51112.2020.9139129

[49] Pranathi Mylavarapu, Adil Yalcin, Xan Gregg, and Niklas Elmqvist. 2019. Ranked-List Visualization: A Graphical Perception Study. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow Scotland Uk, 2019-05-02). ACM, 1–12. https://doi.org/10.1145/3290605.3300422

[50] Ken Nakagaki, Artem Dementyev, Sean Follmer, Joseph A. Paradiso, and Hiroshi Ishii. 2016. ChainFORM: A Linear Integrated Modular Hardware System for Shape Changing Interfaces. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (Tokyo, Japan, 2016-10-16) *(UIST '16)*. Association for Computing Machinery, 87–96. https://doi.org/10.1145/2984511.2984587

[51] Ken Nakagaki, Sean Follmer, and Hiroshi Ishii. 2015. LineFORM: Actuated Curve Interfaces for Display, Interaction, and Constraint. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology - UIST '15* (Daegu, Kyungpook, Republic of Korea, 2015). ACM Press, 333–339. https://doi.org/10.1145/2807442.2807452

[52] Jonas Neubert and Hod Lipson. 2016. Soldercubes: a self-soldering self-reconfiguring modular robot system. *Autonomous Robots* 40, 1 (Jan. 2016), 139–158. https://doi.org/10.1007/s10514-015-9441-4

[53] Martin Nisser, Leon Cheng, Yashaswini Makaram, Ryo Suzuki, and Stefanie Mueller. 2021. Programmable Polarities: Actuating Interactive Prototypes with Programmable Electromagnets. In *The Adjunct Publication of the 34th Annual ACM Symposium on User Interface Software and Technology* (Virtual Event USA, 2021-10-10). ACM, 121–123. https://doi.org/10.1145/3474349.3480198

[54] Chris North, Tim Dwyer, Bongshin Lee, Danyel Fisher, Petra Isenberg, George Robertson, and Kori Inkpen. 2009. Understanding Multi-touch Manipulation for Surface Computing. In *Human-Computer Interaction – INTERACT 2009*, Tom Gross, Jan Gulliksen, Paula Kotzé, Lars Oestreicher, Philippe Palanque, Raquel Oliveira Prates, and Marco Winckler (Eds.). Vol. 5727. Springer Berlin Heidelberg, Berlin, Heidelberg, 236–249. https://doi.org/10.1007/978-3-642-03658-3_31 Series Title: Lecture Notes in Computer Science.

[55] Michael Ortega and Alix Goguey. 2019. BEXHI: A Mechanical Structure for Prototyping Bendable and EXpandable Handheld Interfaces. In *Proceedings of the 2019 ACM International Conference on Interactive Surfaces and Spaces*. ACM, Daejeon Republic of Korea, 269–273. https://doi.org/10.1145/3343055.3359703

[56] Esben Hallundbæk Østergaard, Kristian Kassow, Richard Beck, and Henrik Hautop Lund. 2006. Design of the ATRON lattice-based self-reconfigurable robot. *Autonomous Robots* 21, 2 (01 Sep 2006), 165–183. https://doi.org/10.1007/s10514-006-8546-1

[57] Rizuwana Parween, Anh Vu Le, Yuyao Shi, and Mohan Rajesh Elara. 2020. System Level Modeling and Control Design of hTetrakis–A Polyiamond Inspired Self-Reconfigurable Floor Tiling Robot. *IEEE Access* 8 (2020), 88177–88187. https://doi.org/10.1109/ACCESS.2020.2992333 Conference Name: IEEE Access.

[58] Florian Perteneder, Kathrin Probst, Joanne Leong, Sebastian Gassler, Christian Rendl, Patrick Parzer, Katharina Fluch, Sophie Gahleitner, Sean Follmer, Hideki Koike, and Michael Haller. 2020. Foxels: Build Your Own Smart Furniture. In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction* (New York, NY, USA, 2020-02-09) *(TEI '20)*. Association for Computing Machinery, 111–122. https://doi.org/10.1145/3374920.3374935

[59] Benoit Piranda and Julien Bourgeois. 2018. Designing a quasi-spherical module for a huge modular robot to create programmable matter. (2018), 16.

[60] Benoît Piranda and Julien Bourgeois. 2022. Datom: A Deformable Modular Robot for Building Self-reconfigurable Programmable Matter. In *Distributed Autonomous Robotic Systems*, Fumitoshi Matsuno, Shun-ichi Azuma, and Masahito Yamamoto (Eds.). Springer International Publishing, Cham, 70–81.

[61] Halley P Profita, James Clawson, Scott Gilliland, Clint Zeagler, Thad Starner, Jim Budd, and Ellen Yi-Luen Do. 2013. Don't mind me touching my wrist: a case study of interacting with on-body technology in public. (2013), 8.

[62] Laura Pruszko, Céline Coutrix, Yann Laurillau, Benoît Piranda, and Julien Bourgeois. 2021. Molecular HCI: Structuring the Cross-disciplinary Space of Modular Shape-changing User Interfaces. *Proceedings of the ACM on Human-Computer Interaction* 5, EICS (May 2021), 1–33. https://doi.org/10.1145/3461733

[63] Laura Pruszko, Yann Laurillau, Benoît Piranda, Julien Bourgeois, and Céline Coutrix. 2021. Impact of the Size of Modules on Target Acquisition and Pursuit for Future Modular Shape-changing Physical User Interfaces. In *Proceedings of the 2021 International Conference on Multimodal Interaction* (New York, NY, USA, 2021-10-18) *(ICMI '21)*. Association for Computing Machinery, 297–307. https://doi.org/10.1145/3462244.3479936

[64] Raf Ramakers, Johannes Schöning, and Kris Luyten. 2014. Paddle: highly deformable mobile devices with physical controls. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, Toronto Ontario Canada, 2569–2578. https://doi.org/10.1145/2556288.2557340

[65] Julie Rico and Stephen Brewster. 2010. Usable gestures for mobile interfaces: evaluating social acceptability. (2010), 10.

[66] John W. Romanishin, Kyle Gilpin, Sebastian Claici, and Daniela Rus. 2015. 3D M-Blocks: Self-reconfiguring robots capable of locomotion via pivoting in three dimensions. In *2015 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, Seattle, WA, USA, 1925–1932. https://doi.org/10.1109/ICRA.2015.7139450

[67] John W. Romanishin, Kyle Gilpin, and Daniela Rus. 2013. M-blocks: Momentum-driven, magnetic modular robots. In *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, Tokyo, 4288–4295. https://doi.org/10.1109/IROS.2013.6696971

[68] Anne Roudaut, Abhijit Karnik, Markus Löchtefeld, and Sriram Subramanian. 2013. Morphees: toward high "shape resolution" in self-actuated flexible mobile devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '13* (Paris, France, 2013). ACM Press, 593. https://doi.org/10.1145/2470654.2470738

[69] A. Roudaut, D. Krusteva, M. McCoy, A. Karnik, K Ramani, and S. Subramanian. 2016. Cubimorph: Designing modular interactive devices. In *2016 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, Stockholm, Sweden, 3339–3345. https://doi.org/10.1109/ICRA.2016.7487508

[70] Philipp Schoessler, Daniel Windham, Daniel Leithinger, Sean Follmer, and Hiroshi Ishii. 2015. Kinetic Blocks: Actuated Constructive Assembly for Interaction and Display. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. Association for Computing Machinery, New York, NY, USA, 341–349. https://doi.org/10.1145/2807442.2807453

[71] Florine Simon, Anne Roudaut, Pourang Irani, and Marcos Serrano. 2019. Finding Information on Non-Rectangular Interfaces. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow Scotland Uk, 2019-05-02). ACM, 1–8. https://doi.org/10.1145/3290605.3300332

[72] A. Sprröwitz, R. Moeckel, M. Vespignani, S. Bonardi, and A.J. Ijspeert. 2014. Roombots: A hardware perspective on 3D self-reconfiguration and locomotion with a homogeneous modular robot. *Robotics and Autonomous Systems* 62, 7 (July 2014), 1016–1033. https://doi.org/10.1016/j.robot.2013.08.011

[73] Paul Strohmeier, Jesse Burstyn, Juan Pablo Carrascal, Vincent Levesque, and Roel Vertegaal. 2016. ReFlex: A Flexible Smartphone with Active Haptic Feedback for Bend Input. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction - TEI '16* (Eindhoven, Netherlands, 2016). ACM Press, 185–192. https://doi.org/10.1145/2839462.2839494

[74] L.R. Sudhakar, R.W. Schoenmarklin, S.A. Lavender, and W.S. Marras. 1988. The Effects of Gloves on Grip Strength and Muscle Activity. *Proceedings of the Human Factors Society Annual Meeting* 32, 11 (Oct. 1988), 647–650. https://doi.org/10.1518/107118188786762603

[75] Ryo Suzuki, Junichi Yamaoka, Daniel Leithinger, Tom Yeh, Mark D. Gross, Yoshihiro Kawahara, and Yasuaki Kakehi. 2018. Dynablock: Dynamic 3D Printing for Instant and Reconstructable Shape Formation. In *The 31st Annual ACM Symposium on User Interface Software and Technology - UIST '18*. ACM Press, Berlin, Germany, 99–111. https://doi.org/10.1145/3242587.3242659

[76] Ryo Suzuki, Clement Zheng, Yasuaki Kakehi, Tom Yeh, Ellen Yi-Luen Do, Mark D. Gross, and Daniel Leithinger. 2019. ShapeBots: Shape-changing Swarm Robots. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology (UIST '19)*. Association for Computing Machinery, New York, NY, USA, 493–505. https://doi.org/10.1145/3332165.3347911

[77] Atau Tanaka and R. Benjamin Knapp. 2017. 2002: Multimodal Interaction in Music Using the Electromyogram and Relative Position Sensing. In *A NIME Reader*, Alexander Refsum Jensenius and Michael J. Lyons (Eds.). Vol. 3. Springer International Publishing, Cham, 45–58. https://doi.org/10.1007/978-3-319-47214-0_4 Series Title: Current Research in Systematic Musicology.

[78] Atau Tanaka and R. Benjamin Knapp. 2017. 2002: Multimodal Interaction in Music Using the Electromyogram and Relative Position Sensing. In *A NIME Reader*, Alexander Refsum Jensenius and Michael J. Lyons (Eds.). Vol. 3. Springer International Publishing, Cham, 45–58. https://doi.org/10.1007/978-3-319-47214-0_4 Series Title: Current Research in Systematic Musicology.

[79] Melanie Tory and Robert Kincaid. 2013. Comparing physical, overlay, and touch screen parameter controls. In *Proceedings of the 2013 ACM international conference on Interactive tabletops and surfaces - ITS '13* (St. Andrews, Scotland, United Kingdom, 2013). ACM Press, 91–100. https://doi.org/10.1145/2512349.2512812

[80] Philip Tuddenham, David Kirk, and Shahram Izadi. 2010. Graspables revisited: multi-touch vs. tangible input for tabletop displays in acquisition and manipulation tasks. In *Proceedings of the 28th international conference on Human factors in computing systems - CHI '10* (Atlanta, Georgia, USA, 2010). ACM Press, 2223. https://doi.org/10.1145/1753326.1753662

[81] Benjamin Verdier, Sheldon Andrews, and Paul G. Kry. 2017. Human grasping interaction capture and analysis. In *Proceedings of the ACM SIGGRAPH / Eurographics Symposium on Computer Animation (SCA '17)*. Association for Computing Machinery, New York, NY, USA, 1–2. https://doi.org/10.1145/3099564.3108163

[82] Ryoichi Watanabe, Yuichi Itoh, Masatsugu Asai, Yoshifumi Kitamura, Fumio Kishino, and Hideo Kikuchi. 2004. The Soul of ActiveCube — Implementing a Flexible, Multimodal, Three-Dimensional Spatial Tangible Interface. 2, 4 (2004), 13.

[83] Lining Yao, Ryuma Niiyama, Jifei Ou, Sean Follmer, Clark Della Silva, and Hiroshi Ishii. 2013. PneUI: pneumatically actuated soft composite materials for shape changing interfaces. In *Proceedings of the 26th annual ACM symposium on User interface software and technology - UIST '13*. ACM Press, St. Andrews, Scotland, United Kingdom, 13–22. https://doi.org/10.1145/2501988.2502037

[84] Kentaro Yasu. 2020. MagneLayer: Force Field Fabrication for Rapid Prototyping of Haptic Interactions. In *ACM SIGGRAPH 2020 Labs*. ACM, Virtual Event USA, 1–2. https://doi.org/10.1145/3388763.3407761

[85] Kentaro Yasu and Yuichiro Katsumoto. 2015. Bump ahead: easy-to-design haptic surface using magnet array. In *SIGGRAPH Asia 2015 Emerging Technologies*. ACM, Kobe Japan, 1–3. https://doi.org/10.1145/2818466.2818478

[86] Yiwei Zhao, Lawrence H. Kim, Ye Wang, Mathieu Le Goc, and Sean Follmer. 2017. Robotic Assembly of Haptic Proxy Objects for Tangible Interaction and Virtual Reality. In *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces*. ACM, Brighton United Kingdom, 82–91. https://doi.org/10.1145/3132272.3134143

[87] Clement Zheng, Jeeeun Kim, Daniel Leithinger, Mark D. Gross, and Ellen Yi-Luen Do. 2019. Mechamagnets: Designing and Fabricating Haptic and Functional Physical Inputs with Embedded Magnets. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, Tempe Arizona USA, 325–334. https://doi.org/10.1145/3294109.3295622

[88] Kening Zhu, Morten Fjeld, and Ayça Ünlüer. 2018. WristOrigami: Exploring Foldable Design for Multi-Display Smartwatch. In *Proceedings of the 2018 on Designing Interactive Systems Conference 2018 - DIS '18*. ACM Press, Hong Kong, China, 1207–1218. https://doi.org/10.1145/3196709.3196713

[89] Oren Zuckerman, Saeed Arida, and Mitchel Resnick. 2005. Extending Tangible Interfaces for Education: Digital Montessori-inspired Manipulatives. (2005), 10.

A APPENDIX 1: RESULTS FROM THE QUESTIONNAIRES

		Shape / Strength					
		Cubic			Rounded		
Configuration	Manipulation	0.5	1	2	0.5	1	2
Flat	Lift	6,75	6,85	6,33	4,83	6,33	6,50
	Split 1	6,67	6,46	6,50	6,42	6,42	6,67
	Split 2	6,50	5,85	6,25	5,92	6,17	6,17
	Split Line	5,50	4,92	4,58	4,25	4,58	4,42
	Split Half	6,08	6,38	6,08	5,17	5,33	6,08
	Slide	5,33	5,17	5,00	4,33	5,17	5,00
	Fold	5,67	5,75	5,50	4,83	5,33	5,33
	Bend	4,67	5,08	5,08	4,67	5,83	6,25
Thick	Lift	7,00	6,55	7,00	6,92	6,92	7,00
	Split 1	6,42	5,91	5,17	6,42	6,50	6,33
	Split 2	5,25	4,55	5,00	5,42	5,67	5,83
	Split Line	5,08	5,18	4,33	4,27	4,17	3,50
	Split Half	6,08	6,55	6,67	6,08	6,25	6,67
	Slide	5,67	6,25	5,92	4,69	5,83	5,67

Very difficult (1) — Very easy (7)

(a) Mean Likert score of the difficulty item (*"Overall, how difficult or easy did you find this task?"*).

		Shape / Strength					
		Cubic			Rounded		
Configuration	Manipulation	0.5	1	2	0.5	1	2
Flat	Lift	4,75	5,46	5,00	4,00	5,08	4,92
	Split 1	5,25	5,15	5,42	5,08	5,67	5,50
	Split 2	5,75	5,15	5,58	5,17	5,50	5,25
	Split Line	4,83	4,23	4,42	3,92	4,00	3,83
	Split Half	5,33	5,69	5,50	4,67	4,75	5,25
	Slide	5,00	4,92	5,08	3,92	5,25	4,50
	Fold	5,08	5,50	5,33	4,42	5,17	4,83
	Bend	4,00	4,25	4,33	4,83	5,75	5,92
Thick	Lift	5,17	5,55	5,33	5,42	4,92	5,25
	Split 1	5,50	5,18	4,50	5,25	5,50	5,58
	Split 2	4,67	4,73	4,58	4,50	4,83	5,08
	Split Line	4,83	4,91	4,25	3,64	4,25	3,83
	Split Half	5,42	6,18	6,08	5,50	5,75	5,67
	Slide	5,25	5,50	5,58	4,46	5,33	5,08

Very dissatisfaying (1) — Very satisfaying (7)

(b) Mean Likert score of the satisfaction item (*"Overall, how dissatisfaying or satisfaying did you find this task?"*)

		Shape / Strength					
		Cubic			Rounded		
Configuration	Manipulation	0.5	1	2	0.5	1	2
Flat	Lift	4,33	5,00	5,17	2,58	4,08	4,75
	Split 1	5,33	5,38	5,42	4,67	4,67	5,17
	Split 2	5,83	4,77	5,42	5,00	4,75	5,17
	Split Line	4,17	4,15	3,92	2,92	3,42	3,83
	Split Half	4,58	4,92	4,92	3,83	4,42	5,08
	Slide	3,92	4,08	4,33	3,00	3,92	3,83
	Fold	4,00	4,83	5,33	3,50	4,83	4,67
	Bend	3,50	4,33	4,83	3,25	4,83	5,50
Thick	Lift	4,83	4,82	4,92	4,83	4,75	5,17
	Split 1	5,50	4,18	4,67	5,42	5,25	5,50
	Split 2	4,50	3,64	3,92	3,50	4,92	5,08
	Split Line	4,17	3,55	3,92	2,91	3,50	3,67
	Split Half	4,75	5,00	4,92	4,00	5,33	5,42
	Slide	4,42	5,00	4,83	3,92	5,25	5,00

Very negatively (1) — Very positively (7)

(c) Mean Likert score of the impact of shape item (*"Overall, how did the shape impact the task?"*)

		Shape / Strength					
		Cubic			Rounded		
Configuration	Manipulation	0.5	1	2	0.5	1	2
Flat	Lift	5,08	5,23	4,92	3,08	3,92	3,92
	Split 1	5,17	5,00	5,00	4,67	4,92	5,50
	Split 2	5,42	4,69	5,00	4,42	5,17	5,33
	Split Line	5,00	4,85	4,92	3,50	3,17	3,75
	Split Half	5,50	5,85	5,42	3,33	3,58	4,58
	Slide	5,08	5,33	5,08	3,50	4,50	4,17
	Fold	5,17	5,67	5,08	4,08	4,83	4,50
	Bend	3,08	3,25	3,42	4,83	5,58	6,08
Thick	Lift	5,00	5,00	4,83	4,58	4,50	4,58
	Split 1	4,83	5,09	4,17	5,25	5,33	5,67
	Split 2	4,42	4,36	4,25	4,17	5,25	5,17
	Split Line	4,75	4,64	4,42	3,64	3,83	3,17
	Split Half	5,17	5,73	5,42	4,58	5,00	4,75
	Slide	5,25	6,00	5,25	4,31	4,17	4,50

Very negatively (1) — Very positively (7)

(d) Mean Likert score of the impact of strength item (*"Overall, how did the *strength* impact the task?"*)

Figure 13: We report the mean Likert score for each item in the questionnaire: overall difficulty (13a), overall satisfaction (13b), perceived impact of the strength (13c) and perceived impact of the shape (13d). The scales range from 1 (red - most negative response) to 7 (blue - most positive response) with 4 as the center (grey - neutral).