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

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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.

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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*

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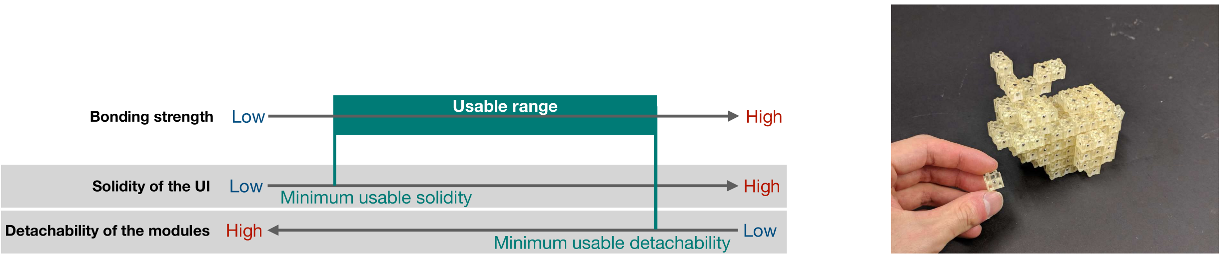


(a) The bonding strength should be low enough so users can detach the modules manually, while strong enough for the UI to hold its shape.

(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.*

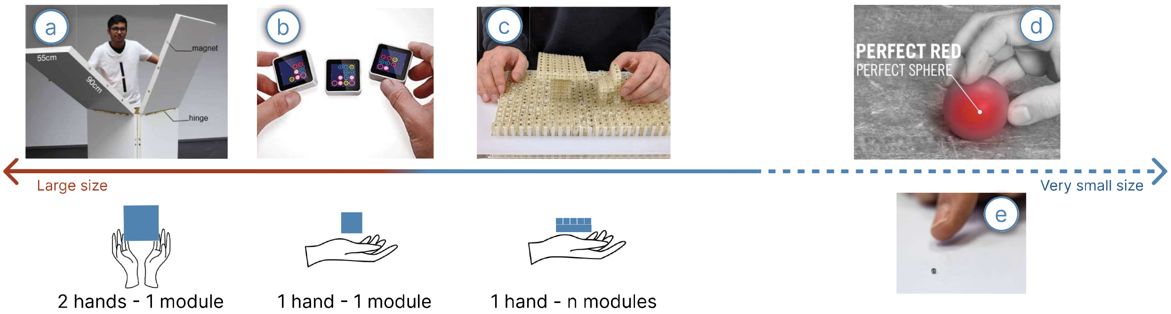


Figure 2: Modular TUIs enable a wide range of interaction modalities and prototypes, e.g. (a) reconfigurable smart VR environment [17], (b) reconfigurable touchscreens [46], or (c) dynamic 3D shape printings [75]. An example long-term vision for such interfaces is (d) Perfect Red [34], with modules as 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].

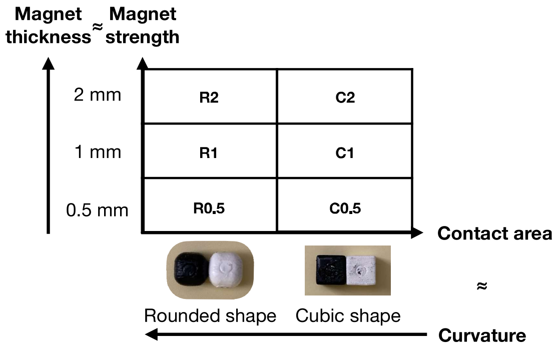
When searching for industry standards, we did not find studies nor guidelines on the detachability/solidity trade-off. We did find safety information related to the strength of magnets, especially on ingestion hazard. The U.S. Consumer Product Safety Commission advises that small magnets used in manipulated 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

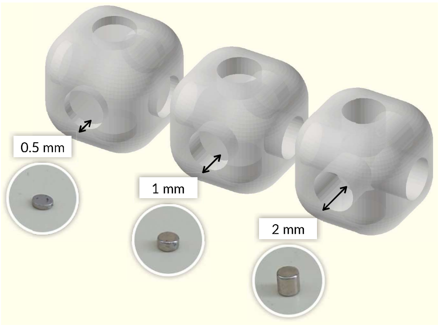
We conducted a controlled user study to investigate three levels of bonding strength between modules and two module shapes when manipulating a modular tangible prototype. We study their impact on eight manipulations from the literature with two different configurations of modules. Our goal is to understand 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.

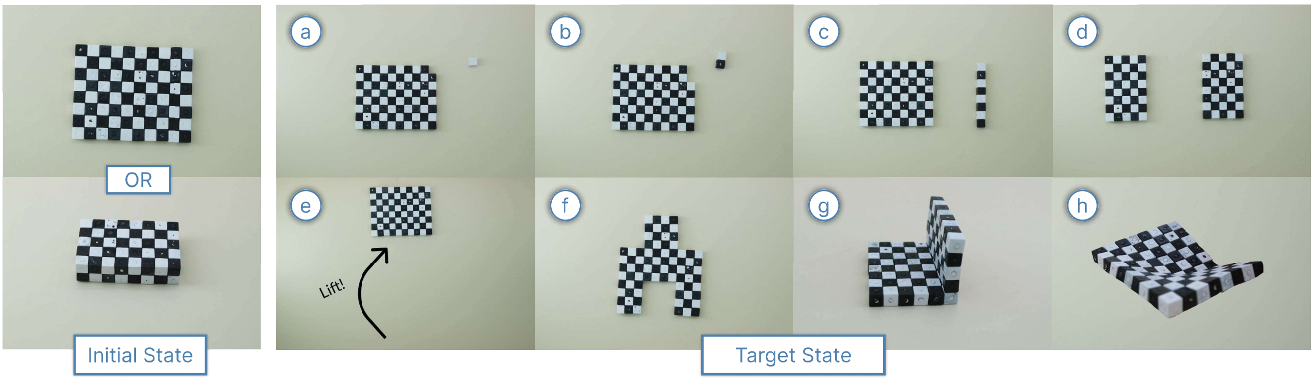


Figure 4: Participants performed manipulations on either a flat configuration, i.e. one layer of 80 modules (top left), or a thick configuration, i.e. two layers of 40 modules each (bottom left). From the prototype in its initial state shown in the left, participants performed eight manipulations (right): (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).

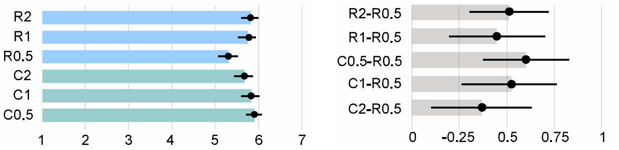
To analyze them, we rely on estimation techniques with 95% confidence intervals (CIs) as recommended by the APA [20] and which is becoming more and more a standard practice in HCI research (e.g., [11, 37, 41, 49, 71]). The effect size is computed between the scores of each questionnaire item for each 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.

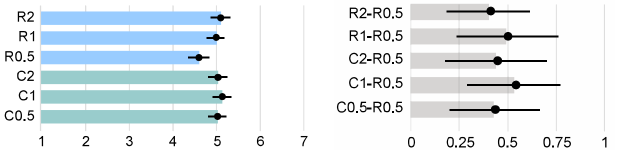
4.1 Overall results

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.*

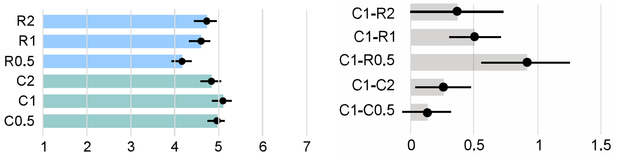
We find evidence that participants rated the rounded modules (Satisfaction = 4.93/7 (1 = very dissatisfying, 7 = very satisfying), CI [4.79, 5.05]) to be overall slightly less satisfying compared to the cubic ones (5.1, CI [4.97, 5.21]). As shown in Figures 5c and 5d, the results show strong evidence 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.

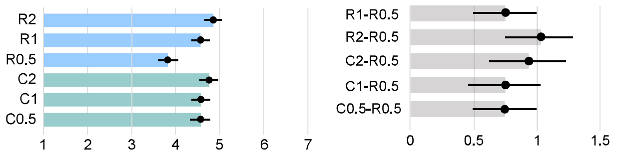
4.1.4 *Impact of the strength.*

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]).

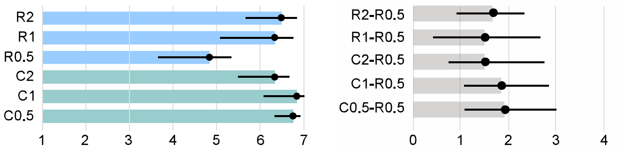
(d) Pairwise comparison to R0.5 (most negative). R2 (most positive) was rated 1.03pt (CI [0.74, 1.28]) higher than R0.5.

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.

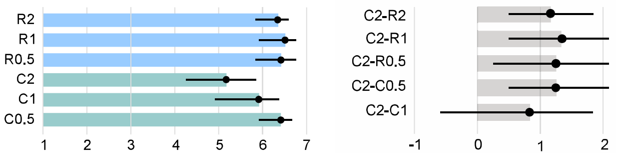
(b) Pairwise comparison to R0.5 (most difficult). C0.5 (the easiest) was rated 1.92pts (CI [1.08, 3.0]) easiest than R0.5.

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]

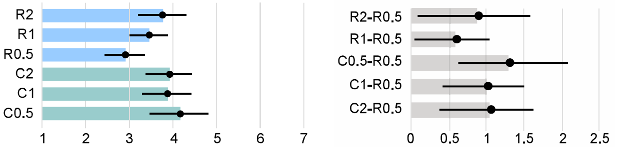
(b) Pairwise comparison to C2. R1 (easiest) was rated 1.33pts (CI [0.5, 2.08]) easier than C2.

(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

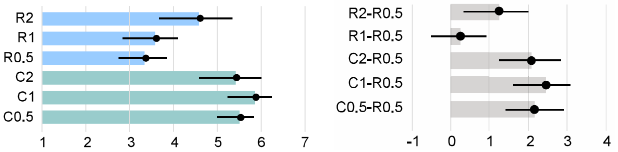
Figure 8: (Top) Mean easiness of splitting 1 module between conditions, for the thick configuration. (Bottom) Mean perceived impact of the strength on splitting 2 module between conditions, for the thick configuration. Error Bars show bootstrapped 95% CIs. (Right) Pairwise comparisons show the effect 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.



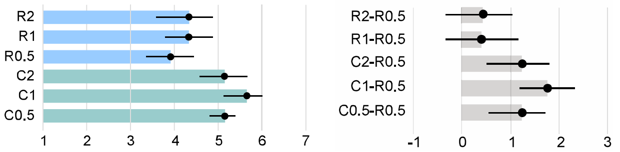
(c) Mean perceived impact of the shape on splitting the UI in half. Lowering the strength worsen the impact of having a rounded shape, with R0.5 rated lowest (3.33, CI [2.75, 3.83]).

(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]).

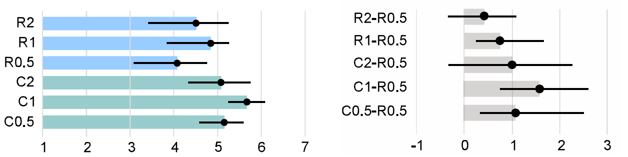


(a) Mean perceived impact of the shape on sliding parts of the UI. R0.5 scored lowest (4.69, CI [3.85, 5.12]) and C1 highest (6.25, CI [5.5, 6.7])

(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"*.

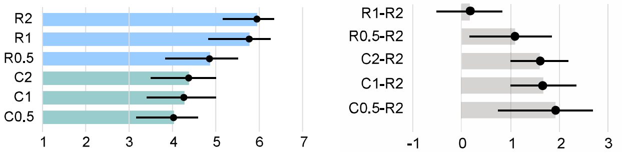


(a) Mean perceived impact of the shape on folding the UI. R0.5 was rated lowest (4.08, CI [3.08, 4.75]) and C1 highest (5.7, CI [5.25, 6.08]).

(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 $6 \times 6 \times 6 mm^3$ prototypes we only used ⌀2mm magnets since the contact area between modules is only $2 \times 2 mm^2$ for rounded modules. The available area for cubic modules, on the other hand, is $6 \times 6 mm^2$. 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.

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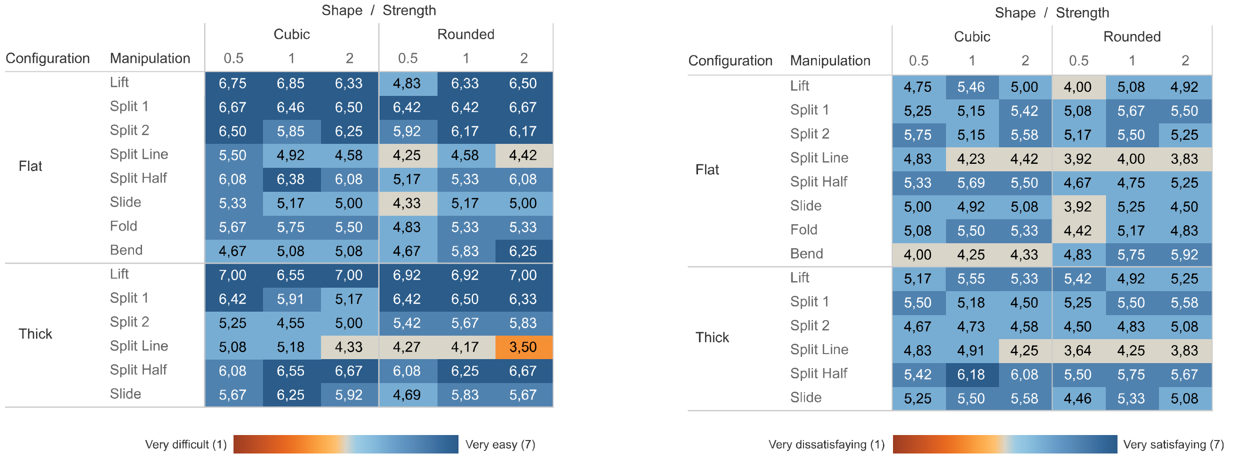
A APPENDIX 1: RESULTS FROM THE QUESTIONNAIRES



Shape / Strength

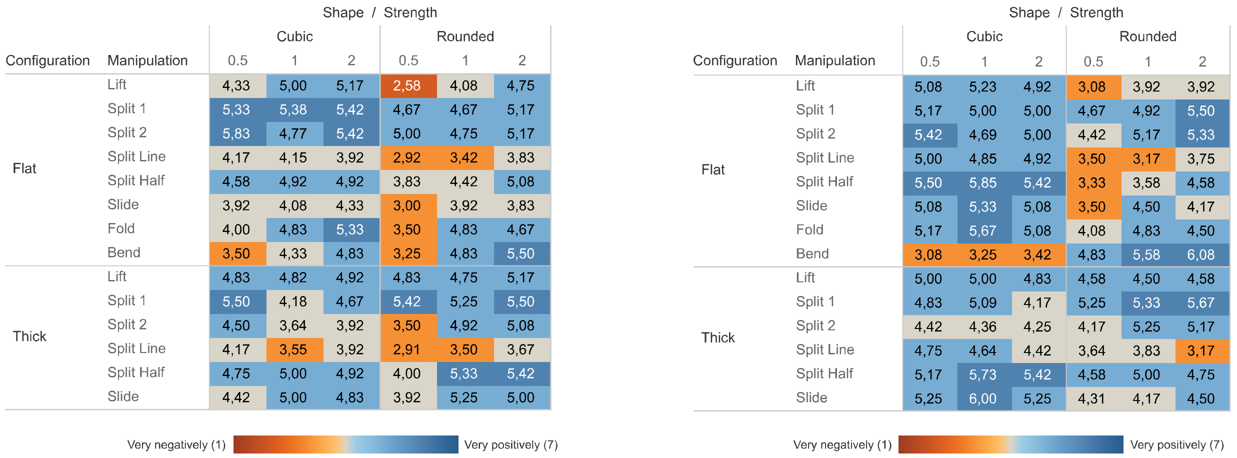
Configuration	Manipulation	Cubic			Rounded		
		0.5	1	2	0.5	1	2
Flat	Lift	6,75	6,85	6,33	4,83	6,33	6,50
	Split 1	6,67	6,46	6,50	6,42	6,42	6,67
	Split 2	6,50	5,85	6,25	5,92	6,17	6,17
	Split Line	5,50	4,92	4,58	4,25	4,58	4,42
	Split Half	6,08	6,38	6,08	5,17	5,33	6,08
	Slide	5,33	5,17	5,00	4,33	5,17	5,00
	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

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

Shape / Strength

Configuration	Manipulation	Cubic			Rounded		
		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

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



Shape / Strength

Configuration	Manipulation	Cubic			Rounded		
		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

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

Shape / Strength

Configuration	Manipulation	Cubic			Rounded		
		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

(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).