ShyPins: Safeguarding User Mental Safety From The Forcible (Dis)Appearance Of Pin-based Controls By Using Speed Zones

Maxime Daniel
Univ. Bordeaux
ESTIA-Institute of Technology, EstiaR
F-64210 Bidart, France
m.daniel@estia.fr

William Delamare
Univ. Bordeaux
ESTIA-Institute of Technology, EstiaR
F-64210 Bidart, France
w.delamare@estia.fr

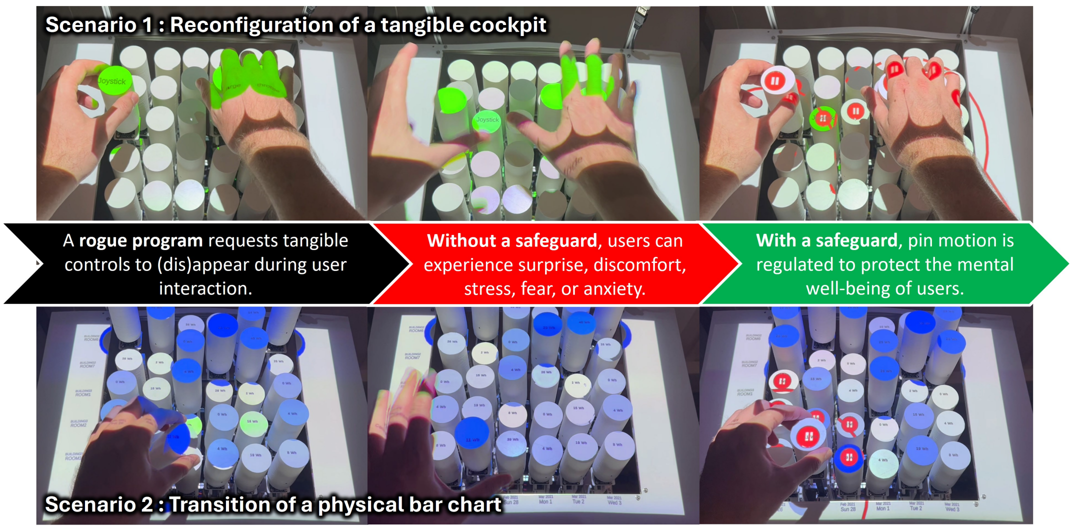

Figure 1: *ShyPins* regulates pin motion to prevent the forcible (dis)appearance of tangible controls, mitigating psychological harm to users during scenarios like reconfiguring a tangible cockpit (top) and transitioning a physical bar chart (bottom).

Abstract

Pin-based shape displays can cause psychological harm by forcefully making tangible controls (dis)appear in contact with users. We present ShyPins, a pin-based shape display regulating pin motion based on proximity to the user's body to prevent such incidents. A first user study reveals that for system-triggered actuation, gradually decreasing pins' speed as users get closer is perceived as safer than pausing pins immediately when users are too close. For user-triggered actuation, the perceived safety of both strategies depends on user preferences. However, pausing a pin motion creates an incoherence between the physical artifact and the digital data. Thus, to inform users about paused pins, the safeguard projects pause icons and stop zones onto the pin-based surface. A second study reveals that projecting user-centered stop zones is perceived safer than pin-centered ones. Additionally, pin-based surfaces are perceived as less safe when users approach pins in motion than when pins approach users.

CCS Concepts

• **Human-centered computing** → **User studies**.

Keywords

Shape-Changing Interfaces, Pin-Based Shape Displays, User Safety.

ACM Reference Format:
Maxime Daniel and William Delamare. 2025. ShyPins: Safeguarding User Mental Safety From The Forcible (Dis)Appearance Of Pin-based Controls By Using Speed Zones. In *Nineteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '25), March 04–07, 2025, Bordeaux / Talence, France.* ACM, New York, NY, USA, 16 pages. https://doi.org/10.1145/3689050.3704940

TEI '25, March 04–07, 2025, Bordeaux / Talence, France

ACM ISBN 979-8-4007-1197-8/25/03
https://doi.org/10.1145/3689050.3704940

1 Introduction

Pin-based shape displays are actuated pin arrays creating interactive physical surfaces: both the system and the user can pull and push pins to physically interact with each other [17, 21, 40, 52, 57]. As demonstrated by Follmer et al. [17], these displays have the capability to make tangible controls appear or disappear on demand through pin actuation (buttons [17], dials [52], handles [17], joysticks [40], sliders [52]).

However, safety is a significant challenge to address before allowing end-users to interact with shape-changing interfaces in real-world scenarios [4, 25, 43, 53]. Any program can request a pin-based shape display, lacking proper safeguards, to make a tangible control appear by forcefully pushing pins into the user's arm or disappear by forcefully pulling pins from the user's hand. Although pin-based shape displays are designed with power and force limitations to prevent physical harm to the user's body, the psychological impact of tangible controls forcefully (dis)appearing in contact with users cannot be overlooked. Indeed, incorrect or unexpected physical interaction of actuated devices with humans can evoke negative emotional responses such as distrust, discomfort, stress, fear, anxiety, and surprise, compromising the perceived safety of such devices [2, 48].

In Robotics, a standard safety measure involves establishing safety speed zones around actuated devices to prevent unintended physical interaction with humans [58–60]. Our proposal extends this concept by implementing safety speed zones around individual pins to prevent the forcible (dis)appearance of tangible controls during user interaction. This ensures that tangible controls only become active when not in close proximity with users and do not cause psychological harm to users. Extensive research has investigated the impact of safety zones on the mental safety of human beings supervising large system-controlled devices such as industrial manipulators [2, 46, 48]. However, it is not clear how safety zones affect the well-being of humans physically interacting with an assembly of small user- or system-controlled devices such as pin-based shape displays. Furthermore, safety zones present a challenge when pausing pin motions, as this can introduce a discrepancy between the physical shape of the display (actual pin height) and the underlying digital data of the application (intended pin height). Solutions such as projecting pause icons and safety zones on the pin-based surface can help notify users about this discrepancy. Prior research has demonstrated that projecting safety zones around a robot effectively communicates reasons for slowdowns or halts [59, 60]. Alternatively, visualizing safety zones around the user's body parts rather than individual pins presents another approach. However, the effectiveness of one approach over the other in enhancing the perceived safety of pin-based shape displays remains unclear.

In this paper, we introduce *ShyPins*, a 5x6 replica of the actuated pin array of the *Emergeables* system [40] enabling various tangible controls to (dis)appear dynamically (e.g., buttons, dials, joysticks). The system incorporates a safeguard that regulates pin motion based on their proximity to the user's body using a motion capture technology. Spatial augmented reality is used to project pause icons and safety zones onto pins that are paused by the safeguard. A first lab study reveals that three speed zones (stop, half speed, full speed) is perceived as safer than two speed zones (stop, full speed) for system-triggered pin motions while the perceived safety of both strategies depends on user preferences for user-triggered pin motions. A second lab study reveals that projecting user-centered stop zones to inform users about paused pins is perceived as safer than pin-centered ones. Lastly, users approaching pins in motion is perceived as less safe than pins approaching a user's body part. Our contributions are:

(1) Knowledge transfer from Robotics focusing on ensuring the physical and mental safety of human beings interacting with actuated devices.
(2) A comparative evaluation of the perceived safety of pin-based shape displays with varying safety zone numbers.
(3) A comparative evaluation of the perceived safety of pin-based shape displays visualizing pin-centered safety zones or, a novel approach, user-centered safety zones.

2 Motivation

Our research aims to prevent situations where the physical controls of a pin-based shape display forcefully appear or vanish when users interact with them, which can cause psychological harm if safeguards are absent. Due to ethical and legal considerations [47], we did not conduct a study on negative human responses to faulty interactions. Instead, we present user scenarios illustrating how psychological harm can manifest: (1) during the physical reconfiguration of an adaptive cockpit, and (2) during the data transition of a physical bar chart.

Scenario 1: Forcible reconfiguration of a tangible cockpit
Sarah, a 32-year-old drone racing enthusiast, works for a company that specializes in rover-assisted drone maintenance for photovoltaic farms. The rovers recharge and deploy drones for solar panel inspections. Sarah trains recruits on the ShyPins display, which features two cockpit modes (Figure 2-a): rover and drone. In rover mode, a joystick with an integrated dial controls the rover's xy-axis movement and z-axis rotation, while in drone mode, there is a joystick for xy-axis translation and z-axis rotation, plus a throttle for z-axis translation. During a training session, Sarah encounters an unexpected problem – a recent application update has introduced a bug. As she reaches to adjust the throttle in drone mode, the glitch suddenly switches the cockpit to rover mode, catching her off guard. In the confusion, her hand gets momentarily caught between shifting controls. This incident leaves Sarah feeling alarmed, disrupting the session and raising concerns about the mental impact on her and her recruits.

Scenario 2: Forcible data transition of a physical bar chart
Emily, a 25-year-old undergraduate passionate about sustainability, is drawn to the ShyPins display in her university's entrance hall—a dynamic bar chart to raise awareness of campus energy consumption (Figure 2-b). The chart visualizes energy use across buildings, with bars that users manipulate to explore days and buildings. Eager to investigate campus energy patterns, she starts interacting with the display, bending bars to navigate the data. However, she quickly notices something strange: each time she bends a bar, the height of all bars, including the one she is holding, updates instantly. This behavior was designed for immediate feedback, but the sudden adjustments surprise and unsettle her. Initially excited, she now feels hesitant, and her unease discourages other passersby from engaging with the display.

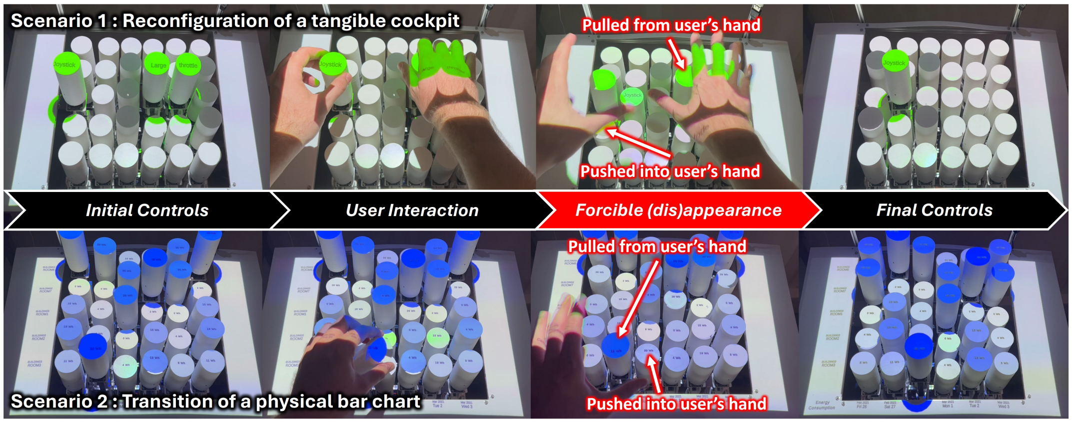

Figure 2: Psychological harm (e.g., discomfort, anxiety, mistrust) can be inflicted to users when a pin-based shape display is allowed to push tangible controls into the user's arm or to pull tangible controls from the user's hand such as during (a) the reconfiguration of an adaptive tangible cockpit or (b) during the data transition of a physical bar chart.

3 Related Work

This work builds on the literature related to (1) ensuring user safety with shape-changing interfaces, (2) the output capabilities of pin-based shape displays subject to safety considerations, and (3) the compliance of pin-based shape displays with safety standards.

3.1 Ensuring User Safety With Shape-Changing Interfaces

Shape-changing interfaces (SCIs) aim to blur the boundary between physical and virtual objects, combining the physicality of Tangible User Interfaces (TUIs) with the malleability of Graphical User Interfaces (GUIs). These actuated devices can perform physical transformations in response to user or system inputs, enabling them to convey information, meaning, or affect [4]. To advance SCIs, Alexander et al. [4] pinpointed twelve key challenges, including ensuring the safe and ethical operation of such devices [4]. In robotics, ensuring user safety has long been a priority, with "safety" referring to the well-being of humans interacting with actuated devices [2, 46, 48]. This includes mitigating device actions that could cause physical harm, such as whipping, slicing, or crushing (referred to as "physical safety"), and guarding against psychological harm, including feelings of distrust, discomfort, stress, fear, anxiety, and surprise (referred to as "mental safety") [2, 46, 48]. Despite concerns about the physical safety of users with SCIs [4, 41, 53], little attention has been given to this issue, especially regarding mental safety. Yet, the perceived safety of actuated devices is crucial for long-term interaction, collaboration, and acceptance [2]: comfort, predictable situations, familiar situations, sense of control, and trust are human factors associated with the safety perception of actuated devices [2].

Device factors influencing the mental safety of humans include distance, speed, distance-speed proportionality, direction of approach, size and appearance, motion fluency and predictability, communication, and smooth contacts [2, 46]. These factors prevent us from directly generalizing previous results involving large manufacturing robots to small actuated devices like pin-based shape displays. Past research has primarily focused on system-controlled actuated devices for collaborative tasks [2, 46] (e.g., industrial manipulators, indoor mobile robots, humanoid robots, drones, autonomous vehicles). In contrast, the SCI community has introduced a wide variety of actuated devices for dynamic physical interaction, with control varying along a continuum between the user and the system [44] (e.g., sparse dots [30], single line [35], sparse lines [55], string array [16], hub and structs [24], voxels [54], layers [65], surfaces [8], and pin array [57]). Consequently, without a straightforward transfer of knowledge from the robotics community to the SCI community, the extent of user mental safety with SCIs remains uncertain.

In our work, we investigate the mental safety of users interacting with actuated pin arrays, also known as pin-based shape displays.

3.2 Output Capabilities of Pin-Based Shape Displays Subject to Safety Considerations

Pin-based shape displays like InFORM [17] are actuated pin arrays creating dynamic physical surfaces: both the system and the user can pull and push pins to physically interact with each other. Previous research [17, 45, 52] has demonstrated the ability of these displays to dynamically render tangible controls through a three-stage process [37]:

(1) *Appearance* – one or more pins are raised from the surface to form a tangible controller.
(2) *Interaction* – once the tangible controller is formed, users can physically interact with it (e.g., touch a track [17], push a button [17], pull an handle [17], rotate a dial [52], move a slider [52], bend a joystick [45]).
(3) *Disappearance* – upon completion of the interaction, the tangible controller disappears by retracting the set of pins used to create it into the surface.

Traditionally, tangible controls on pin-based shape displays appear or disappear through z-axis translation of individual pins [17, 45, 52], or by combining z-axis translation with xy-axis translation and z-axis rotation of the pin matrix [52]. Importantly, new pin output modalities have emerged, allowing for dynamic tangible controls in novel ways, such as xy-axis bending of individual pins [36, 38], z-axis rotation of individual pins [36], and pin inflation [36]. However, it remains unclear how pin output modalities, starting with z-axis translation, should be used to make tangible controls dynamically (dis)appear without causing psychological harm to users. For instance, a poorly implemented or malicious program could request a pin-based shape display to interrupt user interaction by suddenly making a tangible controller disappear through z-axis translation while being held and used by a human – *forcible disappearance of tangible controls*. Similarly, such a program could disrupt user interaction by suddenly making tangible controllers appear through z-axis translation near an already grasped and used tangible controller – *forcible appearance of tangible controls*. These incorrect or unexpected interactions can lead to negative emotional responses such as distrust, discomfort, stress, fear, anxiety, and surprise [2, 48].

Previous work has focused on extending the input and output modalities of pin-based shape displays, with little to no consideration of the perceived safety of these new devices. Our work aims to fill this gap, starting with the most straightforward pin output modality, the z-axis translation, to investigate how to render tangible controls dynamically without causing psychological harm.

3.3 Compliance of Pin-Based Shape Displays With Safety Standards

Ensuring compliance with safety standards is crucial for deploying pin-based shape displays in real-world settings. Existing safety standards focus on guaranteeing the physical safety of human beings interacting with actuated devices, rather than their mental safety, which is not explicitly accounted for [46]. However, mental safety can be improved when physical safety is guaranteed, and thus safety standards actually contribute to improving the perceived safety of actuated systems [46]. The safety standards (ISO/EN: 10218-1/2 and ISO/TS 15066) define four strategies for actuated devices when interacting with human beings [58]:

Two strategies for physical contact

During physical contact with humans, the forces exerted by the actuated device upon the human must remain below thresholds to prevent any physical discomfort or injury – *Power and Force Limiting (PFL)*. For instance, a healthcare robot slowly touching and wiping a patient's forearm with a force lower than 30N [11]. The *Power and Force Limiting (PFL)* strategy creates an active system enabling pin actuation with low maximal speed in contact with and around users. The robot can also activate a passive mode where it compensates its weight to hold its position and get directly touched and guided by the user – *Hand Guiding (HG)*. For instance, a worker's hands guiding a robotic arm to lift and attach an instrumental panel to a vehicle body [39]. The *Hand Guiding (HG)* strategy creates an active idle system, waiting for user inputs.

Two strategies for collision avoidance

Prior to physical contact with humans, a robot at maximal speed can immediately stop its motion if a human gets too close – *Safety-rated Monitored Stop (SMS)*. For instance, a robotic arm moving payloads at maximal speed behind fences immediately stopping its motion when an operator enters [58]. The robot can also gradually decrease its speed as the human gets closer – *Speed and Separation Monitoring (SSM)*. For instance, an autonomous vehicle adapting its speed to the distance from pedestrian crossings [14].

Existing pin-based shape displays usually adopt *PFL and HG* strategies, which preserves the best level of interactivity (i.e., actuation in contact with users and around them) but with a low level of dynamicity (i.e., low maximal speed). However, these pin-based shape displays can still cause fear, surprise, discomfort, or create an unpleasant social situation through incorrect or unexpected pin actuation, such as during the forcible (dis)appearance of tangible controls in contact with users. **Our approach diverges from previous pin-based shape displays by intentionally enforcing *SMS* or *SSM* when rendering tangible controls dynamically.** Under this approach, pins in contact with users remain idle and await user inputs (e.g., push, pull, bend, or rotate), and pin motion is restricted solely to counterbalancing their weight. Once out of contact with users, pin motion can occur while respecting safety speed zones (stop zone and full speed zone for *SMS*, and stop zone, reduced speed zone(s), full speed zone for *SSM*). This deliberate choice eliminates any forcible (dis)appearance of tangible controls, as individual pins are no longer capable of (dis)engaging physical contacts with users.

4 ShyPins System

ShyPins is a 5x6 pin-based shape display, inspired by the *Emergeables* system [45], with pins that support push, pull, rotation, and bending inputs, enabling dynamic (dis)appearance of tangible controls like buttons, dials, and joysticks. nlike *Emergeables*, *ShyPins* includes a safeguard that regulates pin motion based on user proximity, using a Leap Motion Controller. A video projector is used to project pause icons and safety zones onto pins that are paused by the safeguard. Any application can send shape-change objectives to the safeguard (e.g., move pin n°25 from 0 cm to 15 cm in 2 s) and receive notifications about shape-change events from the safeguard (e.g., user proximity to pin n°25 has changed). If the application does not adjust its objectives based on user proximity, the safeguard intervenes, slowing down or pausing pin motion.

Design and Capabilities of Individual Pins

Figure 3-left details the components and assembly of a *ShyPins* pin. The pin is a 10cm tall, 4cm diameter PLA cylinder, capable of 100mm movement along the z-axis in 40 steps of 2.5mm at up to 50mm/s. It can also detect 100mm translation along the z-axis, 360° rotation around the z-axis in 15° increments, and 45° bending over the xy-axis in 1° steps.

Hardware and Software For Pin Array

Figure 3-center illustrates the *ShyPins* assembly. The 5x6 pin

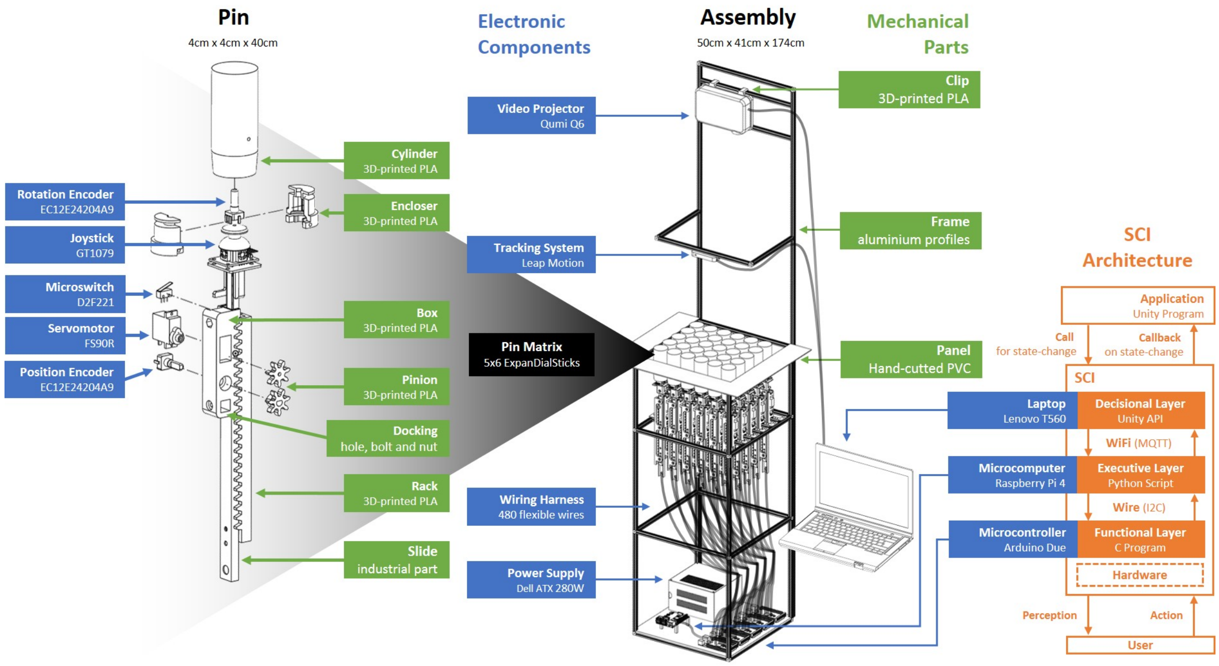

Figure 3: Hardware and software of the ShyPins system.

array, housed in a 50cm x 41cm x 174cm aluminum frame 85cm above the ground, includes a Qumi Q6 video projector 80cm above its rear and a Leap Motion Controller 40cm above its center. A surrounding white PVC panel supports additional projections. The software architecture, shown in Figure 3-right, uses a three-layer robot architecture for decisional autonomy [3]. Below the pin matrix, Five Arduino Due microcontrollers manage 150 electronic components via 480 wires. Each runs a C program as the functional layer, overseeing feedback control loops. All communicate with a Raspberry Pi 4 over I2C. A 750W DTX power supply powers the system. The Raspberry Pi 4 operates as a WiFi Access Point and hosts an MQTT Broker. It runs a Python script as the executive layer, translating objectives from the decisional layer into primitive functions for the functional layer. A laptop, connected to the video projector via HDMI and the tracking system via USB, joins the Raspberry Pi 4 WiFi network. The laptop communicate with the executive layer through the MQTT Broker using a publish/subscribe pattern. It runs a C# Unity script as the decisional layer, which includes both the safeguard and an application. The application sends shape-change objectives to the safeguard (e.g., move pin n°25 from 0cm to 15cm in 2s) and receives notifications about shape-change events (e.g., user proximity to pin n°25 has changed). If the application does not adjust its objectives based on user proximity, the safeguard slows down or pauses pin motion to prevent psychological harm from incorrect or unexpected physical interactions.

5 User Study 1: Perceived Safety of Pin-Based Shape Displays Enforcing Speed Safety Zones

In the realm of collision avoidance strategies, the *Speed and Separation Monitoring (SSM)* strategy (three or more speed zones) is known to enhance the perceived safety of large actuated devices compared to the *Safety-rated Monitored Stop (SMS)* strategy (two speed zones): Mobile service robots [9], autonomous cars [14], and industrial manipulators [28] are perceived as safer when slowing down as they approach humans. However, these findings do not directly apply to pin-based shape displays, where users physically interact with small actuated pins. Various factors, such as the robot's appearance [46], size [23, 42], and user control [2]) influence perceived safety [2, 46]. Therefore, results from large robots cannot be directly transferred to small actuated devices like an actuated pin matrix [2, 46, 48].

In Human-Computer Interaction (HCI), immediate feedback is crucial for ensuring the user's sense of control and maintaining focus [41]. With *SSM* (three or more speed zones), more pins are affected, slowing the overall matrix actuation around the user compared to *SMS* (two speed zones), which can negatively impacts the overall dynamicity of the system. Thus, it is crucial to investigate how the number of speed zones impacts the perceived safety of small robots.

To address this, we conducted a first user study to examine the impact of varying the number of pin speed zones on the perceived safety and dynamicity of pin-based shape displays. This study considered both user-initiated and system-triggered pin motions, such as during the forcible (dis)appearance of tangible controls.

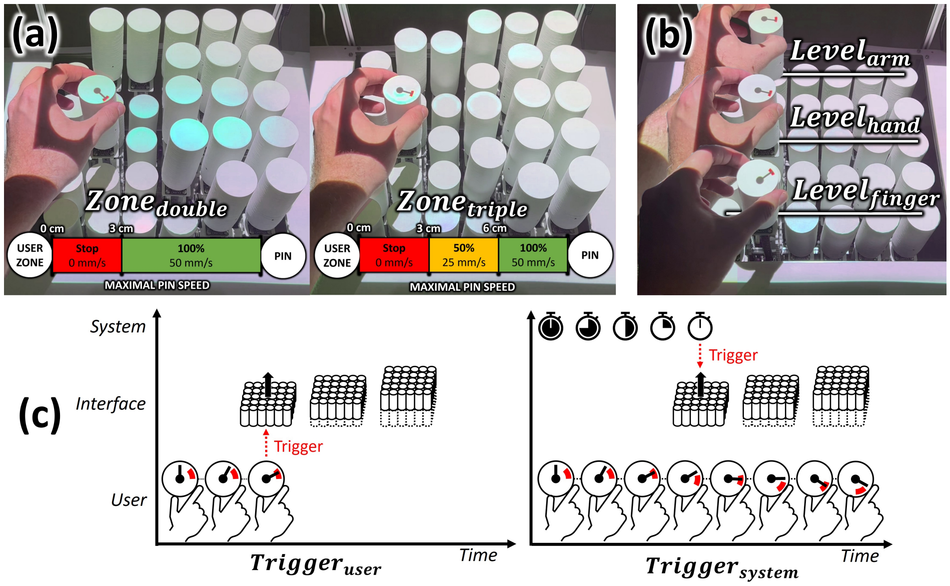

Figure 4: Factors of the first study: the number of pin speed zones (a), the level of user body engagement (b), and the trigger of pin actuation (c).

5.1 Factors

5.1.1 Number of Speed Safety Zones. The ShyPins safeguard perceives the user as virtual spheres and cylinders (i.e., the user zone) enclosing respectively the skeletal hands and forearms generated by the Leap Motion Controller. A radius offset of 3 cm is added to the user zone to (1) ensure that the complete hands and forearms of the user are enclosed and (2) compensate for the tracking error of the Leap Motion Controller [61]. The safeguard restricts the maximum speed of each pin using the following equation:

$$S_{restricted} = max(floor(\frac{D_{observed}}{D_{min}}) \times \frac{1}{N} \times S_{max}, S_{max})$$

where $D_{observed}$ is the distance from the pin's edge to the user's safety zone, D_{min} is the minimal separation distance between a moving pin and the user zone, S_{max} is the maximum speed of a ShyPins pin (50mm/s), and N is the number of zones. We use a minimal separation distance of 3cm (D_{min} = 30mm) which corresponds to the space between the center of one pin and the edge of an adjacent pin. For each standard collision avoidance strategy, we use the following number of discrete separation zones based on common practices in the literature [58] (Figure 4a):

- ($Zone_{double}$) Two separation zones for the *Safety-rated Monitored Stop (SMS)* strategy ($N = 2$, pause zone, full speed zone).
- ($Zone_{triple}$) Three separation zones for the *Speed and Separation Monitoring (SSM)* strategy ($N = 3$, pause zone, half speed zone, full speed zone).

In the worst case scenario, the safeguard halts a ShyPins pin motion at maximum speed (50mm/s) within 15mm in 0.23s.

5.1.2 Level of User Body Engagement. We consider the engagement of the user body over the pin-based surface. Indeed, as the user zone covers more area of the pin matrix, more pins can potentially surround the user's body parts, and hence impacts perceived safety (*distance* factor [46]). We consider three levels (Figure 4b):

- ($Level_{fingers}$) The user engages with their fingers (i.e., target pin in the first row of the matrix).
- ($Level_{hand}$) The user engages with their hand (i.e., target pin is in the middle row of the matrix).
- ($Level_{forearm}$) The user engages with their forearm (i.e., target pin in the last row of the matrix).

5.1.3 Trigger of Pin Actuation. We consider the pin matrix actuation trigger. Indeed, users might perceive safety differently if the shape animation is expected or not (*predictability* factor [46]). We consider two levels (Figure 4c):

- ($Trigger_{user}$) The shape-change is triggered via user input, and hence expected.
- ($Trigger_{system}$) The shape-change is triggered by the system, and hence unexpected.

5.2 Experimental Task

We consider a task with pin actuation triggered either by user input or by system event [44]. The application starts with all pins colored in white in their lowest position. Only the target pin is set to its highest position and displays a black pointer and a red arc, both randomly oriented. Participants have to grasp the target pin, and rotate it so that the pointer enters the red arc (Figure 4). In the $Trigger_{user}$ condition, the application requests an unsafe shape-change as soon as the pointer enters the arc. Participants were asked to keep their hand on the target pin until all moving pins not paused by the safeguard complete their motion. In the $Trigger_{system}$ condition, the application requests an unsafe shape-change after a delay between 5s and 15s after the pointer enters the arc to create an unexpected matrix activation. To simulate a primary task disturbed by a system event, the red arc starts moving once the pointer enters, and participants have to maintain the pointer in the arc before and during the shape-change. Then, the application requests the interface to display all pins in black until there is no more human body presence over the pin array.

The unsafe shape-change simulates a worst-case scenario: the system tries to remove the target pin from the participant's hand, and moves all the other pins to their maximal position (10cm above the surface) at maximal speed (50mm/s). If not mediated by the safeguard, moving pins would entrap the user's hand, and hit user's fingers, palm, and forearm.

5.3 Participants

We recruited 16 participants (8 females, 8 males) on the university campus through mailing lists and public posters. Participation in this study was voluntary and unpaid. Participants had a mean age of 32.5 ± 10.9 years, with a median of 5 years of university education. One participant had previous experience with shape-changing interfaces or robots, having programmed a robotic arm during a student project.

5.4 Apparatus and Procedure

The experiment lasted approximately one hour per participant. We introduced participants to the context of safety with pin matrix actuation, the *ShyPins* system, the objectives to compare two numbers of pin speed zones, and the procedure of the experimentation. We then asked participants to read and to sign an informed consent form, and to fill out a demographic form. After verbal approval, we equipped the Empatica E4 wristband on their non-dominant arm to measure information about stress, fear, anxiety or surprise [46]. Participants wore noise-cancelling headphones to reduce interface's mechanical noise known for adding mental stress [64]. This was done to ensure that we could accurately measure the mental stress generated solely by pin motions, rather than by the noise.

The experiment was conducted in two phases – one for each trigger. Within each phase, the participants completed two sessions – one for each number of pin speed zones. Each session included nine trials – three trials for each level of user body engagement. In total, participants performed $Trigger_2 \times Zone_2 \times Level_3 \times Trial_3 = 36$ trials. A Latin square design was employed to counterbalance the order of trigger, and the order of pin speed zone number for each trigger, addressing potential learning and familiarization effects. The order of user body engagement levels was randomized for each session. To accommodate both left-handed and right-handed participants, the position of the target pin follows a random sequence including three positions (1 per trial): the second column, the fifth column, and the third/fourth columns. Before each trigger, participants were introduced to the task using the ShyPins system and underwent a training session to practice rotating the target pin and aiming the cursor at the red arc (i.e., 9 trials without shape-change). To ensure participants' physiological signals were at rest before each session, a 3-minute relaxation video was played using a flat screen and headphones.

5.5 Variables

To assess users' perceived safety with *ShyPins*, we employed a multi-method approach, as different assessment methods can provide a more reliable evaluation of perceived safety [15, 46]. The methods used are:

- *System events.* During each trial, we logged user inputs (e.g., pin rotation), shape states (e.g., pin position), and application events (e.g., shape-change triggered). This data provides a record of interactions and system responses.
- *Physiological signals.* We recorded two physiological signals during each trial: the electrodermal activity (EDA) and the blood volume pulse (BVP). Using the NeuroKit2 Python library [33], we performed an event-related analysis of these signals: we extracted the maximum Skin Conductance Response (SCR) and the average Heart Rate (HR) features from signals sampled from -1s to +6s after each shape-change.
- *Questionnaires.* After each session, participants completed three items from the GodSpeed questionnaire [7] regarding the perceived safety of the number of pin speed zones.
- *Interviews.* After each phase, we asked participants for their preferences and feedback on the two numbers of pin speed zones: "Do you have a preference for one of the two sessions you just completed? If so, which one and why?". Then, we used an affinity diagram [32] to categorize user feedback and identify common perceptions.

5.6 Results

We removed 35 trials (6%) from the analysis due to missing physiological recordings. Non-parametric tests (Friedman and Wilcoxon tests) were used, with all post-hoc tests reporting Bonferroni corrected p-values. Significant test results are reported ($\alpha \leq 0.05$) with their effect sizes ([F(riedman) or W(ilcoxon) statistic, effect size, p-value]).

We first verified that participants managed to maintain the cursor in the moving red arc during the primary task of the system-triggered pin actuation condition. After a system-triggered pin actuation, users managed to keep the cursor in the moving red arc for 88.69% [86.83, 90.54] of the pin animation time with $Zone_{double}$ and for 89.28% [87.70, 90.86] of the pin animation time with $Zone_{triple}$ ($p > 0.05$).

5.6.1 Level of User Body Engagement.

We did not find any significant results regarding the level of user body engagement on any of the dependent variables (all $p > 0.05$). We hypothesize that the pin matrix of our current prototype may be too small and/or too coarse to create a significant effect on perceived safety, regardless of how far participants' arms extend above the surface.

5.6.2 Trigger of Pin Actuation.

We found a significant main effect of $Trigger$ on all perceived safety items. Participants reported feeling significantly more relaxed [W=59, Z=0.572, p=0.012], more calm [W=59.0, Z=0.572, p=0.012], and less surprised [W=56, Z=0.63, p=0.006] with $Trigger_{user}$ than with $Trigger_{system}$ (Figure 5a). This is supported by skin conductance responses, significantly greater [W=13160, Z=0.2, p=0.006] with $Trigger_{system}$ than with $Trigger_{user}$ (Figure 5b). However, no significant difference was

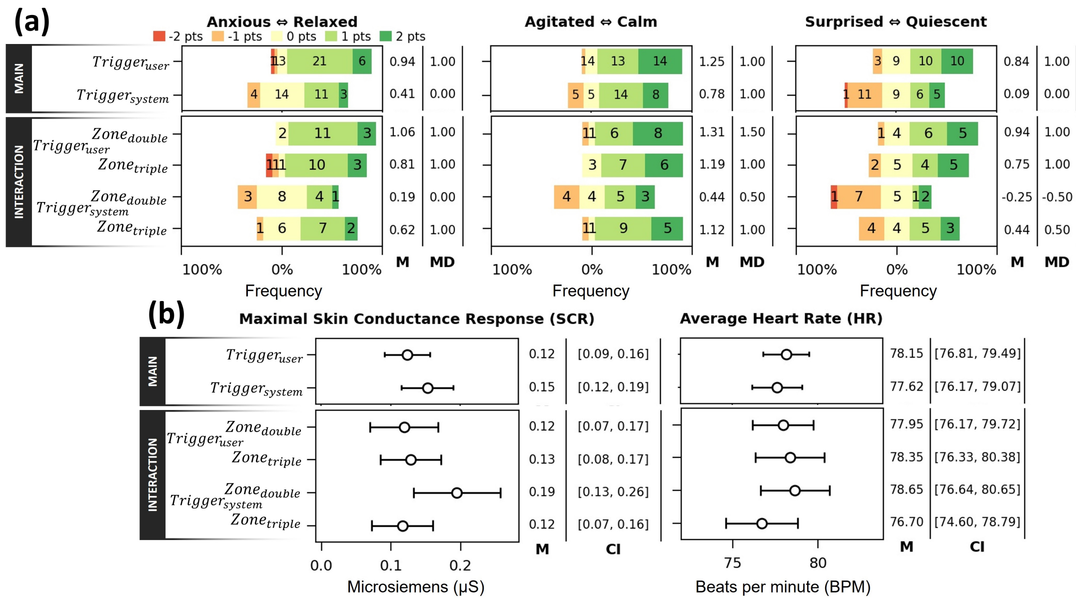

Figure 5: Results of pin actuation triggers (*Trigger*) and pin speed zone numbers (*Zone*) on perceived safety items (a) and physiological signals (b).

found between $Trigger_{user}$ and $Trigger_{system}$ in average heart rate [W=16728, Z=-0.11, p=0.11].

The same effects appear during $Zone_{double}$: Participants reported feeling significantly more relaxed [W=0.0, Z=1.0, p=0.005], more calm [W=0.0, Z=1.0, p=0.03], and less surprised [W=0.0, Z=1.0, p<0.001] with $Trigger_{user}$ than with $Trigger_{system}$ (Figure 5a). However, during $Zone_{triple}$, we did not find a significant difference between $Trigger_{user}$ and $Trigger_{system}$ on the maximal skin conductance response [F=4429, Z=-0.03, p=1.0], the average heart rate [F=4269, Z=-0.16, p=0.40], the level of relaxation [F=28, Z=0.15, p=1.0], the level of surprise [F=37, Z=0.19, p=1.0], or the level of agitation [W=16, Z=-0.11, p=1.0].

These findings validate previous results from the robotics community, which show that a sense of control positively impacts perceived safety [2]. We will next analyze how the perceived safety with each number of pin speed zones is influenced by the actuation trigger.

5.6.3 Number of Speed Safety Zones. We did not find any significant result regarding the pin speed zone number factor on any dependent variables (all $p > 0.05$). Indeed, it appears that with $Trigger_{user}$ (i.e., participants in total control of the shape-changing event), both numbers of pin speed zones are acceptable. The only significant difference between the numbers of pin speed zones was observed with $Trigger_{system}$: participants reported feeling significantly more calm [W=0.0, Z=-1, p=0.04], and less surprised [W=0.0, Z=-1, p=0.04] with $Zone_{triple}$ than with $Zone_{double}$ (Figure 5a). This finding is supported by skin conductance responses, which were significantly greater [W=2453, Z=0.32, p<0.01] with $Zone_{double}$ than with $Zone_{triple}$ (Figure 5b). However, no significant difference was found between $Zone_{double}$ and $Zone_{triple}$ in average heart rate [W=4119, Z=-0.03, p=1.0].

These results validate previous findings from the robotics community [2, 46], demonstrating that *SSM* (three or more speed zones) – with slowed down pins – is perceived as better than *SMS* (two speed zones). However, our results also show that with user-triggered pin motions, there is no significant difference between *SSM* (three or more speed zones) and *SMS* (two speed zones). This suggests that *SMS* could potentially improve dynamicity by not slowing down extra pins around the user's body part.

5.7 Study 1 Discussion

We summarize the results and discuss the main takeaways in light of participants' feedback.

5.7.1 With system-triggered pin motions: Using three speed zones rather than two speed zones improves the perceived safety. Enforcing three speed zones is (1) more calm, (2) less surprising and (3) induces less stress than enforcing two speed zones with system-triggered pin motions. Thirteen participants (81.13%) preferred three speed zones, which slows down and soothes pin motion around the user body, compared to two speed zones (e.g., **P5:** *"During the last session [$Zone_{double}$], the system was faster and more brutal because all pins moved together."*).

Six participants (37.5%) raised that the focus of attention also impacts perceived safety. Indeed, while performing a task in the focus of attention, users were more surprised, distracted, stressed and/or scared by pin matrix actuation happening in their periphery of attention with two speed zones than with three speed zones (e.g., **P2:** *"I preferred earlier [$Zone_{triple}$] because I was less surprised by the system when I was focused [on the task]. I was more surprised here [$Zone_{double}$]."*).

These results interconnect previous works on perceived safety and peripheral interaction supporting (1) that a system-controlled robot motion is perceived safer if it slows down as it approaches humans [46], and (2) that a system-controlled robot motion in user's periphery of attention should be slow and quiet to keep the user focused on the main task [12]. To improve the perceived safety of pin-based shape displays rendering tangible controls dynamically, safeguards should enforce three rather than two speed zones on pin matrix actuation triggered by a system event, especially in user's periphery of attention.

5.7.2 With user-triggered pin motions: Using two or three speed zones depends on user preferences. When pin motion is triggered by a user input, the results reveals that:

- Eight participants (50%) preferred three speed zones for a calm shape-change completion (e.g., **P11:** *"During the first session [$Zone_{triple}$], it was smoother and less stressful than during the last one [$Zone_{double}$]: I like having time to see the motion coming."*). The different pin speeds also created an overall pleasant effect with $Zone_{triple}$ (e.g., **P1:** *"In the last session [$Zone_{triple}$], the robot was smoother and more pleasant to watch [than $Zone_{double}$]."*).
- The other eight participants preferred two pin speed zones for a fast shape-change completion (e.g., **P8:** *"I preferred the first session [$Zone_{double}$] because the system was faster and it did not bother me to wait [until all pin motions were completed around me]. However, I waited too much time during the second session [$Zone_{triple}$] and it annoyed me."*).

These results on pin-based surfaces echo with previous studies arguing that individual human characteristics (personality, gender, experience, culture) and preferences are important factors for the safety perception of actuated devices [46]. To improve the perceived safety of pin-based shape displays rendering tangible controls dynammically, the safeguard should enforce three speed zones to trigger calm pin matrix actuation motion. For users comfortable with the system, the safeguard could use only two speed zones to allow fast shape-change completion, and hence favor dynamicity.

5.7.3 Moving Forward: Addressing Incoherence in Pin State. If the application fails to adjust pin motion to user proximity, the safeguard intervenes by slowing down or pausing pins in the safety zones around the user's body. This situation, especially pin motion in pause, creates an incoherence as the physical model of the interface does not match the virtual model of the application anymore. The safeguard should inform users about pins in an incoherent state and the reasons for this state. The follow-up study focuses on visualization techniques to inform users about paused pins and speed zones. In this follow-up study, we enforced three safety speed zones (SSM) due to its superior perceived safety in system-triggered scenarios, and no significant difference in user-triggered scenarios.

6 Study 2: Perceived Safety Of Pin-Based Shape Displays Using Stop Zone Visualizations

Collision avoidance strategies can create discrepancies between the physical shape of the display (actual pin height) and the corresponding digital data of the application (intended pin height). Prior research has shown that projecting safety zones around a robot effectively communicates reasons for slowdowns or halts [59, 60]. Thus, projecting pause icons and safety zones on the pin-based surface can help notify users about these discrepancies. However, the robotics community recognizes the need for a more user-centered approach to safety [13]. In HCI, visualizing safety zones around user's body parts, rather than individual pins, could offer a novel approach. The effectiveness of this method in enhancing the perceived safety of pin-based shape displays remains to be explored.

We conducted a second study to compare the perceived safety of user-centered versus pin-centered stop zone visualizations on pin-based shape displays. This comparison focused on situations where the safeguard needs to inform users about paused pin motions, such as during the forcible (dis)appearance of tangible controls.

6.1 Factors

6.1.1 Stop Zone Visualization. We designed two visualization techniques to project information onto the pin-based surface, informing users about paused pins and explaining why these pins have been paused. Both techniques (Figure 6a) project a red dot and a white pause icon on each paused pin, along with a 1cm-wide red circle representing the minimal separation distance (D_{min} radius):

- ($Visual_{pin}$) Displays a stop zone around each paused pin (*pin-centered approach*).
- ($Visual_{user}$) Displays a stop zone around the user's body (*user-centered approach*).

Both visualizations represent the same minimal separation distance between the user and the pin (D_{min}), known as the stop zone. However, while $Visual_{user}$ displays a single stop zone around the user's body, $Visual_{pin}$ displays a stop zone for each paused pin. To prevent visual overload, $Visual_{pin}$ removes the inner edges of intersecting zones.

Design Rationale. Both visualizations are based on the safety overlay proposed by Vogel et al. [60], which uses a 4 cm-wide red line to indicate the stop zone around an industrial robot (Figure 7-left). We adapted the overlay for *ShyPins* to reduce occlusion with the application's visuals. For $Visual_{pin}$ (Figure 7-right), the adjustments were: (1) Removed inner edges of overlapping stop zones around paused pins to reduce visual clutter, adding a "pause" icon for clarity; (2) Reduced the red line thickness from 4 cm to 1 cm to avoid covering a 4 cm-diameter pin; (3) Added a 25 mm-wide white outline to ensure contrast when application visuals included red tones. For $Visual_{user}$ (Figure 7-center), we applied the same overlay but visualized the stop zone around the user zone instead of individual pins.

6.1.2 Pin Matrix Actuation Density. We consider the density of the pin matrix actuation as a second factor, as it defines the number of moving pins that can potentially be paused (*size* factor [46]). We define three density levels, excluding the target pin (Figure 6b):

- ($Density_{33\%}$) 9 pins are actuated, evenly distributed across the matrix.
- ($Density_{66\%}$) 19 pins are actuated, evenly distributed across the matrix.
- ($Density_{100\%}$) the remaining 29 pins in the matrix are actuated.

6.1.3 Shape-Change Interruption. We explore two instances of shape-change interruption events (Figure 6c), where either the

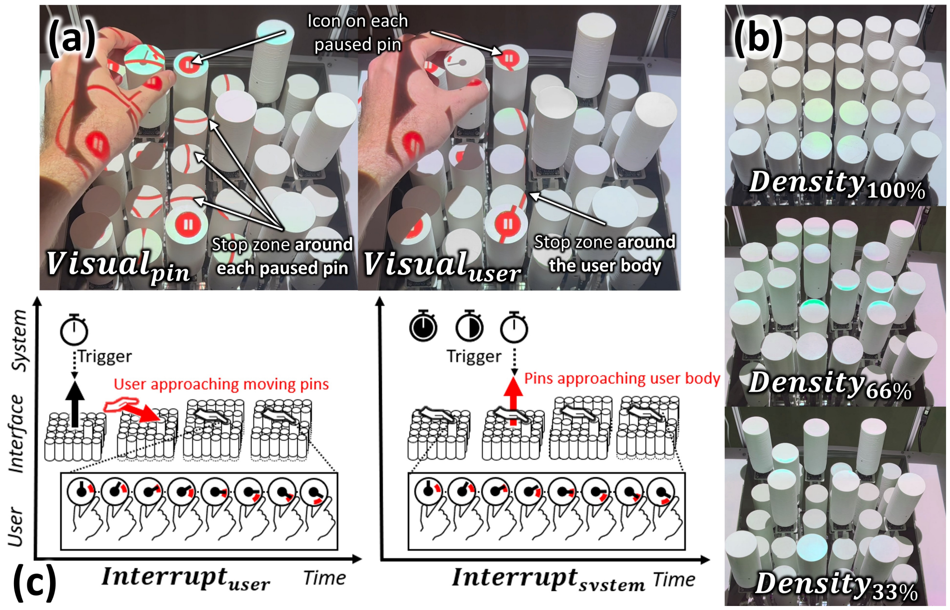

Figure 6: Factors of the second study: the stop zone visualization (a), the pin matrix actuation density (b), and the shape-change interruption event (c).

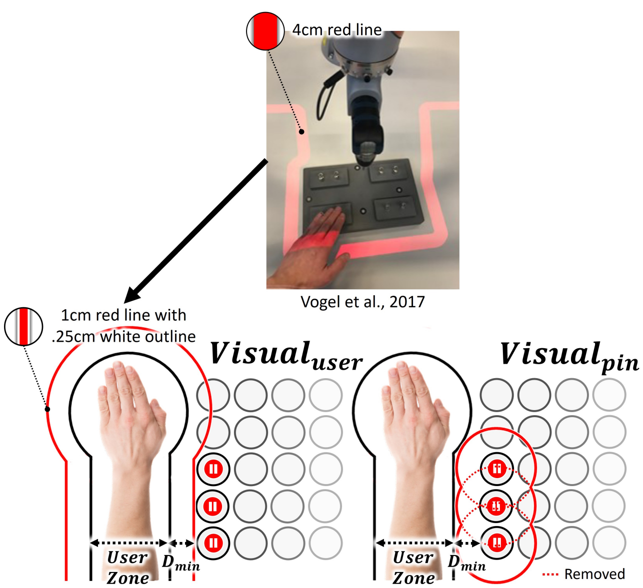

Figure 7: Design of the $Visual$ factor.

system commands or the user movements induce a pause in pin motion (*predictability* factor [46]):

- ($Interrupt_{user}$) The user intentionally brings their body within the minimum separation distance from moving pin(s). For example, if the application is moving a pin upward and the user places a hand above it (i.e., user approaching moving pins).
- ($Interrupt_{system}$) The application intentionally causes pin(s) to come within the minimum separation distance from a user body part. For example, if the user already has a hand above a pin and the application requests the pin to move upward (i.e., pins approaching the user).

6.2 Experimental Task

We use the same task as study 1. Participants are required to reach a target pin, which displays a black pointer and a red arc, and adjust the pin's rotation to position the pointer within the red arc (Figure 6). Participants were informed that the task was a pretext for interacting with the system and were instructed to focus on the shape change, moving and paused pins, and zone visualizations. In the $Interrupt_{user}$ condition, the system triggers the shape change at the beginning of the trial. Participants must reach the target pin (among the moving pins) *during* the shape change, which requires them to navigate around moving pins and the target pin itself to complete the rotation task. In the $Interrupt_{system}$ condition, the system triggers the shape change 6 to 15 seconds after participants begin rotating the target pin. The system continuously rotates the arc, requiring participants to adjust the pointer's rotation *during* the shape change, which results in interruptions from pins getting closer to their forearm and hand. The target pin is randomly positioned in the fourth row of the pin matrix to ensure that at least one pin will be paused under the user's forearm. In all conditions, pin motion duration is set to 6 seconds to give participants enough time to reach the target.

6.3 Participants

We recruited 16 participants (8 females, 8 males) on the university campus through mailing lists and public posters. Participation in this study was voluntary and unpaid. None of the participants had been involved in the first user study The participants had a mean age of 30.3 ± 6.5 years old, with a median of 5 years of university education. None had prior experience with physical interactions involving shape-changing interfaces or robots.

6.4 Apparatus and Procedure

The apparatus and procedure were identical to those used in the first study Each participant went through two phases – one for each interruption type. In each phase, participants completed two sessions – one for each visualization technique. Within each session, participants performed nine trials – three trials for each density level. This results in a total of $Interrupt_2 \times Visual_2 \times Density_3 \times Trial_3 = 36$ trials per participant. Trials were randomly ordered within each session. To accommodate both left-handed and right-handed participants, the target pin's position followed a random sequence across three locations (one per trial): the second column, the fifth column, and the third/fourth columns. To ensure participants' physiological signals were at rest before each session, a 3-minute relaxation video was played using a flat screen and headphones.

6.5 Variables

We reused the dependent variables of the first study, with the exception of the questionnaires. Since visual factors (i.e., stop zone visualizations) might have more subtle effects on users' safety perception compared to physical factors (e.g., collision avoidance strategies), we replaced the GodSpeed questionnaire with the more sensitive Perceived Safety Questionnaire of Akalin et al. [1]. This questionnaire includes eight items rated on a 5-points Likert scale: our items assess participants' feelings during the interaction (e.g., anxious/relaxed), and four items characterize the robot itself (e.g., threatening/safe). Additionally, we employed the Short User Experience Questionnaire (UEQ-S [50]), which includes eight items on a 7-points Likert scale. The UEQ-S assesses both the hedonic quality (four items, e.g., boring/exciting) and the pragmatic quality (four items, e.g., confusing/clear) of each visualization technique.

6.6 Results

No trials were removed from the analysis, as all recordings were complete. We applied the same statistical analysis and reporting methods as in the first study. We first verified that participants managed to perform the primary task of the system-triggered interruption condition. Users successfully maintained the cursor in the moving red arc for 87.69% [82.52, 92.86] of the pin animation time with $Visual_{pin}$ and for 91.70% [88.17, 95.23] of the pin animation time with $Visual_{user}$ ($p > 0.05$).

6.6.1 Density Level. We did not find any significant effects of density level on any of the dependent variables (all $p > 0.05$). We hypothesize that, similar to the first study, the current prototype's pin matrix may be either too small or too coarse to significantly impact perceived safety.

6.6.2 Interruption Type. The interruption type did not have a significant effect on the questionnaire results (all $p > 0.05$). However, there was a significant main effect of $Interrupt$ on average heart rate, with participants' heart rates significantly greater [W=14592.0, Z=-0.299, p<0.001] during $Interrupt_{user}$ than during $Interrupt_{system}$ (Figure 8c). No significant difference was found in skin conductance response between $Interrupt_{user}$ and $Interrupt_{system}$ [W=15478, Z=-0.05, p=0.47].

6.6.3 Visualization Technique. No significant difference was found between $Visual_{user}$ and $Visual_{pin}$ in skin conductance response [W=15231, Z=-0.07, p=0.30] or in heart rate [W=20406, Z=-0.02, p=0.78]. However, a significant main effect of $Visual$ was observed on four perceived safety items and four user experience items.

Participants felt significantly more comfortable [W=45, Z=0.571, p=0.022] and more in control [W=34, Z=0.602, p=0.023] with $Visual_{user}$ than with $Visual_{pin}$. In addition, participants perceived the interface as significantly more familiar [W=22.5, Z=0.669, p=0.011] and more calm [W=18.0, Z=0.735, p=0.008] with $Visual_{user}$ than with $Visual_{pin}$ (Figure 8a).

When it comes to inform users about paused pins and stop zones, participants significantly characterized the interface as more supportive [W=44.0, Z=0.62, p=0.012], easier to use [W=22.5, Z=0.78, p=0.002], more efficient [W=35.5, Z=0.74, p=0.001], and clearer [W=57.5, Z=0.617, p=0.008] with $Visual_{user}$ than with $Visual_{pin}$ (Figure 8b).

6.7 Study 2 Discussion

We summarize the results and discuss the main takeaways in light of participants' feedback.

6.7.1 Projecting user-centered stop zones rather than pin-centered ones to inform users about paused pins. A *user-centered* stop zone follows a single user's body part to reveal its effect range on paused pins, while a pin-centered zone shows the effect range of a single paused pin relative to the user's body part. User-centered stop zones, the novel approach proposed in this paper:

(1) Are preferred by participants. Eleven participants (68.75%) preferred $Visual_{user}$ to $Visual_{pin}$ (e.g., **P14:** *"In the first session [$Visual_{user}$], I had only one circle to watch while I had as many circles to watch as there was cylinders in pause in the last session [$Visual_{pin}$]."*). Note that three participants (18.75%) preferred $Visual_{pin}$, which can ease the detection of paused pins (three participants, e.g., **P11:** *"In the last session [$Visual_{pin}$], there was a direct circle around the cylinders in pause and it was more visible."*).
(2) Improve user's feeling of safety (four participants, e.g., **P3:** *"I felt more secured in the last session [$Visual_{user}$] because I had the feeling that nothing could happen to me inside the zone."*) , and feeling of control (four participants, e.g., **P0:** *"I found the system more controllable in the first session [$Visual_{user}$] because there was only one circle: the one following my hand."*).
(3) Reduce the chance of disturbing user's adjacent tasks compared to *pin-centered* stop zones (six participants e.g., **P8:** *"In the first session [$Visual_{pin}$], the circles overlapped the task sometimes which was annoying."*). Indeed, projecting zones over the surface of multiple actuated devices (i.e., pins) at the same time can spread over the surfaces of neighboring actuated devices (e.g., other pins) and hence potentially disturb the user.

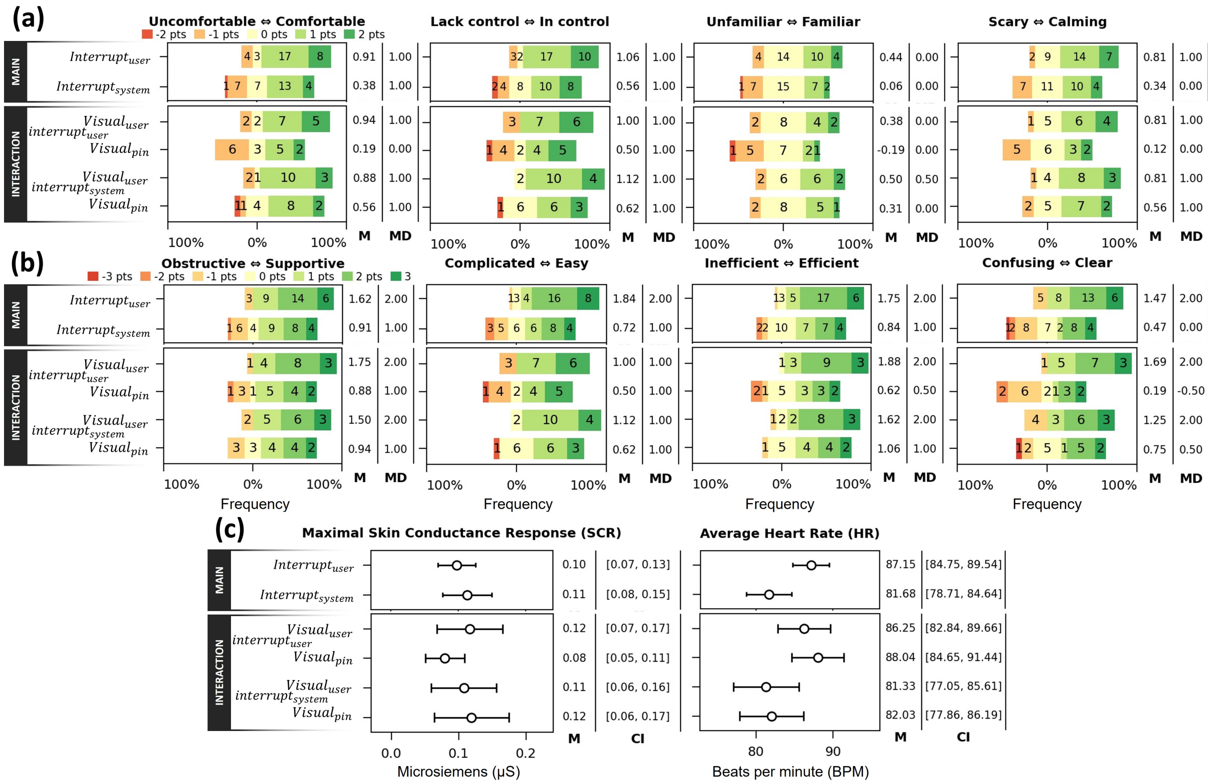

Figure 8: Results of interruption typ3es (*Interrupt*) and stop zone visualisations (*Visual*) on perceived safety items (a), user experience items (b), and physiological signals (c).

6.7.2 Users approaching pins in motion is perceived less safe than pins approaching users. When approaching pins in motion, users felt more stress and anxiety than having pins in motion approaching them. The intention of the shape display was not clear to them and its behavior was hard to predict when users approached pins in motion (3 participants, e.g., **P6:** *"The first two sessions [$Interrupt_{user}$] were more stressful than the last two [$Interrupt_{system}$]. It is not easy to predict the robot behavior when it is already moving. We do not know how the system will react when we move towards it."* , **P7:** *"During these sessions [$Interrupt_{user}$], I was more anxious because I needed to reach the target while the cylinders were still moving."*). The desire for explainability and predictability are essential for the perception of safety [15]: clear robot's intentions contribute to the perceived safety [51]. Previous works used visual cues to communicate the motion intent of robots [5, 56, 62] (e.g., by continuously visualizing a drone's trajectory using AR headsets [62]). While such visual cues help users anticipate and predict robot's directional motion, they partially or completely occlude the robot. However, the surface of SCIs is commonly used as an output modality for displaying application information via a GUI. Thus, there is a design challenge in communicating shape-change intents using the interface's visual output modality potentially already use by the GUI.

7 Main takeaways

From the two user studies, we understand that:

- Enforcing *three speed zones* with system-triggered pin motions rather than *two speed zones* improves the perceived safety.
- Enforcing *two speed zones* or *three speed zones* with user-triggered pin motions depends on user preferences.
- Visualizing a single *user-centered stop zone* rather than multiple *pin-centered stop zones* improves the perceived safety.
- Users approaching pins in motion is perceived as less safe than pins approaching users.

8 Limitations and Perspectives

8.1 A First Step into the Concept of Perceived Safety with SCIs

We performed two controlled laboratory experiments to get insights on the perceived safety of an unfamiliar actuated interface. There are several factors to explore to get a truly comprehensive overview of safety concepts such as *population-*, *context-*, and *implementation*-related factors.

Population factors. Participants never experienced a shape-changing interface before ShyPins (novelty effect), and knew that the experimenter was always present in case of problems (experimental observer effect). Both effects are known to limit the true reactions of humans interacting with actuated devices [2]. In addition, we had a relatively small sample size of a highly-educated young adult population. Future work should also explore individual characteristics factors such as personality traits (e.g., neuroticism, pessimism, and optimism), gender, age, education, experience, or culture to evaluate the safety perception of SCIs [2, 27]. Lastly, in-depth evaluations in the wild of shape-change interfaces are important to assess suitable contexts of use, the fit between tasks and interfaces, and the cultural appropriation of shape-change [4]. With safeguards in place, evaluations in the wild can responsibly proceed, allowing users to freely interact with these actuated interfaces.

Contextual factors. In both studies, participants used a single hand to physically interact with a pin-based surface, and always faced the pin matrix actuation. In addition, the pin-based surface was a small shape display with low matrix resolution and large pins. Yet, other contexts can lead to different results [46]. For instance, (1) the greater distance between the human and the actuated device, the safer the device is perceived, (2) some directions of approach (e.g., from the back rather than from the front) are perceived as less safe, and (3) actuated devices that are larger or with certain features (e.g., shape and color) are perceived as less safe, regardless of their motion [46].

Implementation factors. A ShyPins pin can move at a maximal speed of 0.05m/s, while other comfortable speed thresholds are equal to 0.5m/s for industrial manipulators [6], and in the 0.5–0.7m/s range for drones [22, 63], for example. Yet, dynamic physical interaction can benefit from faster shape-change. Thus, there is a challenge in identifying the trade-off between (i) faster shape-change like other large actuated devices (10 times faster than ours and other recent prototypes [18, 20, 21]), and (ii) the perceived safety. In addition, ShyPins' safeguard reduces pin motion speed using a discrete number of separation zones (0% - 100% speed zones with *SMS* and 0% - 50% - 100% speed zones with *SSM*). Future work should explore how the discretization and the resulting velocity profiles influence the perceived safety of SCIs. For instance, a single continuous separation zone [29] might lead to smoother pin motion and thereby improve the perceived safety of pin-based shape displays.

8.2 Safeguard and Prototyping Perspectives

We describe two research perspectives regarding both the *safeguard visualization* and the *safeguard behavior*.

Safeguard Visualization. The usability and the perceived safety of shape-changing surfaces can benefit from the 3D visualization of safety volumes using AR headsets [19, 49]. Indeed, the human body and actuated pins moves in 3D, enforcing separation zones between them basically creates safety volumes. In the second user study, we used spatial augmented reality to project only the safety zones' edges onto the shape-changing surface. While this approach displays only the necessary information to explain why a pin is paused and prevents users from wearing additional devices, it reduces safety volumes to safety lines.

Besides the safety zones visualization, some participants felt stressed or anxious because the intention of the pin-based shape display was not clear to them: its behavior was hard to predict when they were approaching pins in motion. On could explore if extra-apparatus such as AR headset can help solve the intention problem.

Safeguard behavior. Our first study shows that safety perception of shape-changing interfaces can be improved by adapting shape-change to user's visual attention and emotions:

- *Periphery of attention or System-controlled actuation*: slow pin motions are perceived safer than fast motions.
- *User-controlled actuation*: speed of pin motion can be adapted to users' profile.

A promising perspective is to use machine and deep learning with SCIs to estimate and predict users' mental states (e.g., visual attention [31], fear [10]) from external measures (e.g., head orientation, eye movement, facial expression) and/or internal measures (e.g., brain activity, galvanic skin response, heart rate). For instance, a safeguard knowing user's visual attention and emotions could improve the perceived safety of a pin-based shape display by automatically enforcing a greater speed limitation (1) on a fast system-controlled pin motion happening in user's periphery of attention, or (2) on a user-controlled pin motion in the focus of attention that previously triggered a negative response from users.

8.3 Implications for the SCI community

As noted by Alexander et al. [4], passive acceptance of safety standards from the robotics community may result in guidelines that do not align with the goals of shape-changing interfaces, thereby limiting the dynamic physical interaction these systems aim to provide. Therefore, the SCI community must address the following questions:

(1) **What makes a shape-change mentally unsafe?** This question requires understanding the factors that contribute to mental discomfort during dynamic physical interaction, which recent works in robotics have comprehensively reviewed [2, 46]. However, it is essential to investigate whether mental discomfort is universally experienced across all types of shape-changing interfaces. Indeed, while this work highlights that perceived safety is in fact a relevant question with pin-based shape displays, the SCI community has created various interface types such as line-based [35], string-based [16], and swarm-based [30] to name a few. For example, larger line-based interfaces have been observed to startle users when quickly changing form [35]. In addition, we also should account for various tasks (e.g., rendering tangible controls, simulating material properties), environments (e.g., at home, at work), and users (e.g., novice, expert). Understanding these variables will help in developing tailored safety standards that accommodate the capabilities of shape-changing interfaces.

(2) **How can we predict when a requested shape-change is going to be mentally unsafe?** Predicting mental unsafety involves identifying specific triggers or scenarios that may lead to mental discomfort. This may include sudden or unexpected changes in shape (slow versus fast pin motion around user), perceived loss of control (system versus user-triggered pin motion), or interaction (unforced versus forced pin motion in contact with the user) that evoke anxiety or stress. Developing self-learning agents, predictive models or heuristics based on

empirical data and user feedback will be crucial in foreseeing potentially unsafe interaction before they occur (e.g., predicting that the requested pin-based tangible control rendering will be too fast or too close for user's preferences) [66].

(3) **How can we mitigate a requested shape-change predicted as mentally unsafe while minimizing the impact on dynamic physical interaction?** Mitigation strategies must balance ensuring mental safety with preserving the dynamic capabilities of SCIs. In this work, we chose to explore standard collision avoidance strategies alone (i.e., slowing and stopping pin motions). However, there are other complementary options. For instance, path planning [26, 34] could be explored to handle shape-changes (e.g., z-axis translation of actuated pins, xy-axis bending of actuated lines [35], xy-axis translation of actuated dots [37]) predicted as mentally unsafe by (i) avoiding the user if possible, and (ii) stopping if avoidance fails. In addition to contribute to the safety topic, such options will also imply advancements in SCI prototype capabilities (e.g., enabling active xy-axis bending and translation of individual pins to deviate their trajectory), representing significant technical contributions.

9 Conclusion

In this paper, we highlight that a pin-based shape display, lacking proper safeguards, can forcefully push pins into a user's arm or pull pins from the user's hand, making tangible controls appear or disappear unexpectedly. To address this issue, we introduce ShyPins – a 5x6 pin-based shape display with a safeguard that regulates pin motion based on proximity to the user's body by enforcing speed safety zones. In a first lab study, we compared user safety perceptions of a pin-based shape display using two or three speed zones. We found that for system-triggered pin actuation, three speed zones are preferred and perceived as safer than two. However, for user-triggered pin actuation, preferences vary based on individual characteristics: some users favoring two zones for quick motions and others preferring three for calmer motions. Pausing pin motions can create an discrepancy between the pins' state and the digital data they should represent (e.g., when a physical bar chart partially rendered due to paused pins). Thus, in a second lab study, we compared user safety perceptions of a pin-based shape display projecting *human-centered* or *pin-centered* stop zones onto a pin-based surface to inform users about the discrepancy i.e., paused pins. We found that a single *human-centered* stop zone is preferred and perceived as safer than multiple *pin-centered* stop zones: it improves users' feeling of safety and control, and reduces users' mental workload and visual distraction. Additionally, users perceive pin-based shape displays as less safe when approaching moving pins (unpredictable intent) compared to when pins approach body parts.

Acknowledgments

This Project is financed by the Interreg Atlantic Area Program through the European Regional Development Fund (ERDF) from the European Commission.

References

[1] Neziha Akalin, Annica Kristoffersson, and Amy Loutfi. 2019. Evaluating the Sense of Safety and Security in Human–Robot Interaction with Older People. In *Social Robots: Technological, Societal and Ethical Aspects of Human-Robot Interaction*, Oliver Korn (Ed.). Springer International Publishing, Cham, 237–264. https://doi.org/10.1007/978-3-030-17107-0_12 Series Title: Human–Computer Interaction Series.

[2] Neziha Akalin, Annica Kristoffersson, and Amy Loutfi. 2022. Do you feel safe with your robot? Factors influencing perceived safety in human-robot interaction based on subjective and objective measures. *International Journal of Human-Computer Studies* 158 (Feb. 2022), 102744. https://doi.org/10.1016/j.ijhcs.2021.102744

[3] R. Alami, R. Chatila, S. Fleury, M. Ghallab, and F. Ingrand. 1998. An Architecture for Autonomy. *The International Journal of Robotics Research* 17, 4 (April 1998), 315–337. https://doi.org/10.1177/027836499801700402

[4] 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 *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Association for Computing Machinery, Montreal QC, Canada, 1–14. https://doi.org/10.1145/3173574.3173873

[5] Rasmus S. Andersen, Ole Madsen, Thomas B. Moeslund, and Heni Ben Amor. 2016. Projecting robot intentions into human environments. In *2016 25th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*. IEEE, New York, NY, USA, 294–301. https://doi.org/10.1109/ROMAN.2016.7745145

[6] T. Arai, R. Kato, and M. Fujita. 2010. Assessment of operator stress induced by robot collaboration in assembly. *CIRP Annals* 59, 1 (2010), 5–8. https://doi.org/10.1016/j.cirp.2010.03.043

[7] Christoph Bartneck, Dana Kulić, Elizabeth Croft, and Susana Zoghbi. 2009. Measurement Instruments for the Anthropomorphism, Animacy, Likeability, Perceived Intelligence, and Perceived Safety of Robots. *International Journal of Social Robotics* 1, 1 (Jan. 2009), 71–81. https://doi.org/10.1007/s12369-008-0001-3

[8] Christoph H. Belke and Jamie Paik. 2017. Mori: A Modular Origami Robot. *IEEE/ASME Transactions on Mechatronics* 22, 5 (Oct. 2017), 2153–2164. https://doi.org/10.1109/TMECH.2017.2697310

[9] Christopher Brandl, Alexander Mertens, and Christopher M. Schlick. 2016. Human-Robot Interaction in Assisted Personal Services: Factors Influencing Distances That Humans Will Accept between Themselves and an Approaching Service Robot: Human-Robot Interaction in Assisted Personal Services. *Human Factors and Ergonomics in Manufacturing & Service Industries* 26, 6 (Nov. 2016), 713–727. https://doi.org/10.1002/hfm.20675

[10] Oana Bălan, Gabriela Moise, Alin Moldoveanu, Marius Leordeanu, and Florica Moldoveanu. 2020. An Investigation of Various Machine and Deep Learning Techniques Applied in Automatic Fear Level Detection and Acrophobia Virtual Therapy. *Sensors* 20, 2 (Jan. 2020), 496. https://doi.org/10.3390/s20020496

[11] Tiffany L. Chen, Chih-Hung Aaron King, Andrea L. Thomaz, and Charles C. Kemp. 2014. An Investigation of Responses to Robot-Initiated Touch in a Nursing Context. *International Journal of Social Robotics* 6, 1 (Jan. 2014), 141–161. https://doi.org/10.1007/s12369-013-0215-x

[12] Maxime Daniel, Guillaume Rivière, and Nadine Couture. 2019. CairnFORM: a Shape-Changing Ring Chart Notifying Renewable Energy Availability in Peripheral Locations. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction - TEI '19*. ACM Press, Tempe, Arizona, USA, 275–286. https://doi.org/10.1145/3294109.3295634

[13] Francesco De Pace, Federico Manuri, Andrea Sanna, and Claudio Fornaro. 2020. A systematic review of Augmented Reality interfaces for collaborative industrial robots. *Computers & Industrial Engineering* 149 (Nov. 2020), 106806. https://doi.org/10.1016/j.cie.2020.106806

[14] Debargha Dey, Marieke Martens, Berry Eggen, and Jacques Terken. 2019. Pedestrian road-crossing willingness as a function of vehicle automation, external appearance, and driving behaviour. *Transportation Research Part F: Traffic Psychology and Behaviour* 65 (Aug. 2019), 191–205. https://doi.org/10.1016/j.trf.2019.07.027

[15] Eric Eller and Dieter Frey. 2019. Psychological Perspectives on Perceived Safety: Social Factors of Feeling Safe. In *Perceived Safety*, Martina Raue, Bernhard Streicher, and Eva Lermer (Eds.). Springer International Publishing, Cham, 43–60. https://doi.org/10.1007/978-3-030-11456-5_4 Series Title: Risk Engineering.

[16] Severin Engert, Konstantin Klamka, Andreas Peetz, and Raimund Dachselt. 2022. STRAIDE: A Research Platform for Shape-Changing Spatial Displays based on Actuated Strings. In *CHI Conference on Human Factors in Computing Systems*. ACM, New Orleans LA USA, 1–16. https://doi.org/10.1145/3491102.3517462

[17] Sean Follmer, Daniel Leithinger, Alex Olwal, Akimitsu Hogge, and Hiroshi Ishii. 2013. inFORM: Dynamic Physical Affordances and Constraints Through Shape and Object Actuation. In *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology (UIST '13)*. ACM, New York, NY, USA, 417–426. https://doi.org/10.1145/2501988.2502032 event-place: St. Andrews, Scotland, United Kingdom.

[18] Eric J Gonzalez, Eyal Ofek, Mar Gonzalez-Franco, and Mike Sinclair. 2021. X-Rings: A Hand-mounted 360° Shape Display for Grasping in Virtual Reality. In *The 34th Annual ACM Symposium on User Interface Software and Technology*. ACM, Virtual Event USA, 732–742. https://doi.org/10.1145/3472749.3474782

[19] Uwe Gruenefeld, Lars Prädel, Jannike Illing, Tim Stratmann, Sandra Drolshagen, and Max Pfingsthorn. 2020. Mind the ARm: realtime visualization of robot motion intent in head-mounted augmented reality. In *Proceedings of the Conference on Mensch und Computer*. ACM, Magdeburg Germany, 259–266. https://doi.org/10.1145/3404983.3405509

[20] John Hardy, Christian Weichel, Faisal Taher, John Vidler, and Jason Alexander. 2015. ShapeClip: Towards Rapid Prototyping with Shape-Changing Displays for Designers. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems - CHI '15*. ACM Press, Seoul, Republic of Korea, 19–28. https://doi.org/10.1145/2702123.2702599

[21] Seungwoo Je, Hyunseung Lim, Kongpyung Moon, Shan-Yuan Teng, Jas Brooks, Pedro Lopes, and Andrea Bianchi. 2021. Elevate: A Walkable Pin-Array for Large Shape-Changing Terrains. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. ACM, Yokohama Japan, 1–11. https://doi.org/10.1145/3411764.3445454

[22] Walther Jensen, Simon Hansen, and Hendrik Knoche. 2018. Knowing You, Seeing Me: Investigating User Preferences in Drone-Human Acknowledgement. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, Montreal QC Canada, 1–12. https://doi.org/10.1145/3173574.3173939

[23] Waldemar Karwowski and Mansour Rahimi. 1991. Worker selection of safe speed and idle condition in simulated monitoring of two industrial robots. *Ergonomics* 34, 5 (May 1991), 531–546. https://doi.org/10.1080/00140139108967335

[24] Yuichiro Katsumoto. 2020. Inside Out. In *ACM SIGGRAPH 2020 Art Gallery (SIGGRAPH '20)*. Association for Computing Machinery, New York, NY, USA, 467. https://doi.org/10.1145/3386567.3388556 event-place: Virtual Event, USA.

[25] Hyunyoung Kim. 2018. Fostering Design Process of Shape-Changing Interfaces. In *The 31st Annual ACM Symposium on User Interface Software and Technology Adjunct Proceedings - UIST '18 Adjunct*. ACM Press, Berlin, Germany, 224–227. https://doi.org/10.1145/3266037.3266131

[26] Dana Kulić and Elizabeth Croft. 2007. Pre-collision safety strategies for human-robot interaction. *Autonomous Robots* 22 (2007), 149–164.

[27] Przemyslaw A. Lasota, Terrence Fong, and Julie A. Shah. 2017. A Survey of Methods for Safe Human-Robot Interaction. *Foundations and Trends® in Robotics* 5, 4 (2017), 261–349. https://doi.org/10.1561/2300000052

[28] Przemyslaw A. Lasota, Gregory F. Rossano, and Julie A. Shah. 2014. Toward safe close-proximity human-robot interaction with standard industrial robots. In *2014 IEEE International Conference on Automation Science and Engineering (CASE)*. IEEE, Taipei, 339–344. https://doi.org/10.1109/CoASE.2014.6899348

[29] Przemyslaw A. Lasota and Julie A. Shah. 2015. Analyzing the Effects of Human-Aware Motion Planning on Close-Proximity Human–Robot Collaboration. *Human Factors: The Journal of the Human Factors and Ergonomics Society* 57, 1 (Feb. 2015), 21–33. https://doi.org/10.1177/0018720814565188

[30] 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 *Proceedings of the 29th Annual Symposium on User Interface Software and Technology - UIST '16*. ACM Press, Tokyo, Japan, 97–109. https://doi.org/10.1145/2984511.2984547

[31] Xiangdong Li, Yifei Shan, Wenqian Chen, Yue Wu, Praben Hansen, and Simon Perrault. 2021. Predicting user visual attention in virtual reality with a deep learning model. *Virtual Reality* 25, 4 (Dec. 2021), 1123–1136. https://doi.org/10.1007/s10055-021-00512-7

[32] Andrés Lucero. 2015. Using Affinity Diagrams to Evaluate Interactive Prototypes. In *Human-Computer Interaction – INTERACT 2015*, Julio Abascal, Simone Barbosa, Mirko Fetter, Tom Gross, Philippe Palanque, and Marco Winckler (Eds.). Vol. 9297. Springer International Publishing, Cham, 231–248. https://doi.org/10.1007/978-3-319-22668-2_19 Series Title: Lecture Notes in Computer Science.

[33] Dominique Makowski, Tam Pham, Zen J. Lau, Jan C. Brammer, François Lespinasse, Hung Pham, Christopher Schölzel, and S. H. Annabel Chen. 2021. NeuroKit2: A Python toolbox for neurophysiological signal processing. *Behavior Research Methods* 53, 4 (Aug. 2021), 1689–1696. https://doi.org/10.3758/s13428-020-01516-y

[34] Debasmita Mukherjee, Kashish Gupta, Li Hsin Chang, and Homayoun Najjaran. 2022. A survey of robot learning strategies for human-robot collaboration in industrial settings. *Robotics and Computer-Integrated Manufacturing* 73 (2022), 102231.

[35] 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*. ACM, Charlotte NC USA, 333–339. https://doi.org/10.1145/2807442.2807452

[36] Ken Nakagaki, Yingda (Roger) Liu, Chloe Nelson-Arzuaga, and Hiroshi Ishii. 2020. TRANS-DOCK: Expanding the Interactivity of Pin-based Shape Displays by Docking Mechanical Transducers. In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, Sydney NSW Australia, 131–142. https://doi.org/10.1145/3374920.3374933

[37] Ken Nakagaki, Jordan L Tappa, Yi Zheng, Jack Forman, Joanne Leong, Sven Koenig, and Hiroshi Ishii. 2022. (Dis)Appearables: A Concept and Method for Actuated Tangible UIs to Appear and Disappear based on Stages. In *CHI Conference on Human Factors in Computing Systems*. ACM, New Orleans LA USA, 1–13. https://doi.org/10.1145/3491102.3501906

[38] Akira Nakayasu. 2016. Luminescent Tentacles: A Scalable SMA Motion Display. In *Adjunct Proceedings of the 29th Annual ACM Symposium on User Interface Software and Technology* (Tokyo, Japan) *(UIST '16 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 33–34. https://doi.org/10.1145/2984751.2985695

[39] Yu Ogura, Masakazu Fujii, Kazuyuki Nishijima, Hiroki Murakami, Mitsuharu Sonehara, and IHI Corporation, 1 Shin-Nakahara-cho, Isogo-ku, Yokohama-shi, Kanagawa 235-8501, Japan. 2012. Applicability of Hand-Guided Robot for Assembly-Line Work. *Journal of Robotics and Mechatronics* 24, 3 (June 2012), 547–552. https://doi.org/10.20965/jrm.2012.p0547

[40] Jennifer Pearson, Simon Robinson, Matt Jones, and Céline Coutrix. 2017. Evaluating deformable devices with emergent users. In *Proceedings of the 19th International Conference on Human-Computer Interaction with Mobile Devices and Services*. ACM, Vienna Austria, 1–7. https://doi.org/10.1145/3098279.3098555

[41] 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

[42] Mansour Rahimi and Waldemar Karwowski. 1990. Human perception of robot safe speed and idle time. *Behaviour & Information Technology* 9, 5 (Sept. 1990), 381–389. https://doi.org/10.1080/01449299008924252

[43] Majken Kirkegård Rasmussen and Fabian Hemmert. 2019. Envisioning Future Challenges and Possibilities for Shape-Changing Interfaces through Speculative Scenarios. In *Proceedings of Mensch und Computer 2019 (MuC'19)*. Association for Computing Machinery, New York, NY, USA, 487–492. https://doi.org/10.1145/3340764.3344444

[44] Majken Kirkegård Rasmussen, Timothy Merritt, Miguel Bruns Alonso, and Marianne Graves Petersen. 2016. Balancing User and System Control in Shape-Changing Interfaces: a Designerly Exploration. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction - TEI '16*. ACM Press, Eindhoven, Netherlands, 202–210. https://doi.org/10.1145/2839462.2839499

[45] Simon Robinson, Céline Coutrix, Jennifer Pearson, Juan Rosso, Matheus Fernandes Torquato, Laurence Nigay, and Matt Jones. 2016. Emergeables: Deformable Displays for Continuous Eyes-Free Mobile Interaction. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, San Jose California USA, 3793–3805. https://doi.org/10.1145/2858036.2858097

[46] Matteo Rubagotti, Inara Tusseyeva, Sara Baltabayeva, Danna Summers, and Anara Sandygulova. 2022. Perceived safety in physical human–robot interaction—A survey. *Robotics and Autonomous Systems* 151 (May 2022), 104047. https://doi.org/10.1016/j.robot.2022.104047

[47] Maha Salem, Gabriella Lakatos, Farshid Amirabdollahian, and Kerstin Dautenhahn. 2015. Towards Safe and Trustworthy Social Robots: Ethical Challenges and Practical Issues. In *Social Robotics*, Adriana Tapus, Elisabeth André, Jean-Claude Martin, François Ferland, and Mehdi Ammi (Eds.). Vol. 9388. Springer International Publishing, Cham, 584–593. https://doi.org/10.1007/978-3-319-25554-5_58 Series Title: Lecture Notes in Computer Science.

[48] Pericle Salvini, Diego Paez-Granados, and Aude Billard. 2021. On the Safety of Mobile Robots Serving in Public Spaces: Identifying gaps in EN ISO 13482:2014 and calling for a new standard. *ACM Transactions on Human-Robot Interaction* 10, 3 (Sept. 2021), 1–27. https://doi.org/10.1145/3442678

[49] Ane San Martín and Johan Kildal. 2019. Audio-visual AR to Improve Awareness of Hazard Zones Around Robots. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*. ACM, Glasgow Scotland Uk, 1–6. https://doi.org/10.1145/3290607.3312996

[50] Martin Schrepp, Andreas Hinderks, and Jörg Thomaschewski. 2017. Design and Evaluation of a Short Version of the User Experience Questionnaire (UEQ-S). *International Journal of Interactive Multimedia and Artificial Intelligence* 4, 6 (2017), 103. https://doi.org/10.9781/ijimai.2017.09.001

[51] Emrah Akin Sisbot, Luis F. Marin-Urias, Xavier Broquère, Daniel Sidobre, and Rachid Alami. 2010. Synthesizing Robot Motions Adapted to Human Presence: A Planning and Control Framework for Safe and Socially Acceptable Robot Motions. *International Journal of Social Robotics* 2, 3 (Sept. 2010), 329–343. https://doi.org/10.1007/s12369-010-0059-6

[52] Alexa F. Siu, Eric J. Gonzalez, Shenli Yuan, Jason Ginsberg, Allen Zhao, and Sean Follmer. 2017. shapeShift: A Mobile Tabletop Shape Display for Tangible and Haptic Interaction. In *Adjunct Publication of the 30th Annual ACM Symposium on User Interface Software and Technology - UIST '17*. ACM Press, Québec City, QC, Canada, 77–79. https://doi.org/10.1145/3131785.3131792

[53] Miriam Sturdee and Jason Alexander. 2018. Analysis and Classification of Shape-Changing Interfaces for Design and Application-based Research. *Comput. Surveys* 51, 1 (Jan. 2018), 2:1–2:32. https://doi.org/10.1145/3143559

[54] 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 *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*. ACM, Berlin Germany, 99–111. https://doi.org/10.1145/3242587.3242659

[55] 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* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 493–505. https://doi.org/10.1145/3332165.3347911

[56] Daniel Szafir, Bilge Mutlu, and Terry Fong. 2015. Communicating Directionality in Flying Robots. In *Proceedings of the Tenth Annual ACM/IEEE International Conference on Human-Robot Interaction*. ACM, Portland Oregon USA, 19–26. https://doi.org/10.1145/2696454.2696475

[57] Faisal Taher, Yvonne Jansen, Jonathan Woodruff, John Hardy, Kasper Hornbaek, and Jason Alexander. 2017. Investigating the Use of a Dynamic Physical Bar Chart for Data Exploration and Presentation. *IEEE Transactions on Visualization and Computer Graphics* 23, 1 (Jan. 2017), 451–460. https://doi.org/10.1109/TVCG.2016.2598498

[58] Valeria Villani, Fabio Pini, Francesco Leali, and Cristian Secchi. 2018. Survey on human–robot collaboration in industrial settings: Safety, intuitive interfaces and applications. *Mechatronics* 55 (Nov. 2018), 248–266. https://doi.org/10.1016/j.mechatronics.2018.02.009

[59] Christian Vogel, Markus Fritzsche, and Norbert Elkmann. 2016. Safe human-robot cooperation with high-payload robots in industrial applications. In *2016 11th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*. IEEE, Christchurch, New Zealand, 529–530. https://doi.org/10.1109/HRI.2016.7451840

[60] Christian Vogel, Christoph Walter, and Norbert Elkmann. 2017. Safeguarding and Supporting Future Human-robot Cooperative Manufacturing Processes by a Projection- and Camera-based Technology. *Procedia Manufacturing* 11 (2017), 39–46. https://doi.org/10.1016/j.promfg.2017.07.127

[61] Aleš Vysocký, Stefan Grushko, Petr Oščádal, Tomáš Kot, Ján Babjak, Rudolf Jánoš, Marek Sukop, and Zdenko Bobovský. 2020. Analysis of Precision and Stability of Hand Tracking with Leap Motion Sensor. *Sensors* 20, 15 (July 2020), 4088. https://doi.org/10.3390/s20154088

[62] Michael Walker, Hooman Hedayati, Jennifer Lee, and Daniel Szafir. 2018. Communicating Robot Motion Intent with Augmented Reality. In *Proceedings of the 2018 ACM/IEEE International Conference on Human-Robot Interaction*. ACM, Chicago IL USA, 316–324. https://doi.org/10.1145/3171221.3171253

[63] Anna Wojciechowska, Jeremy Frey, Sarit Sass, Roy Shafir, and Jessica R. Cauchard. 2019. Collocated Human-Drone Interaction: Methodology and Approach Strategy. In *2019 14th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*. IEEE, Daegu, Korea (South), 172–181. https://doi.org/10.1109/HRI.2019.8673127

[64] Alexander Yeh, Photchara Ratsamee, Kiyoshi Kiyokawa, Yuki Uranishi, Tomohiro Mashita, Haruo Takemura, Morten Fjeld, and Mohammad Obaid. 2017. Exploring Proxemics for Human-Drone Interaction. In *Proceedings of the 5th International Conference on Human Agent Interaction*. ACM, Bielefeld Germany, 81–88. https://doi.org/10.1145/3125739.3125773

[65] S Yim, C Sung, S Miyashita, D Rus, and S Kim. 2018. Animatronic soft robots by additive folding. *The International Journal of Robotics Research* 37, 6 (May 2018), 611–628. https://doi.org/10.1177/0278364918772023

[66] Angeliki Zacharaki, Ioannis Kostavelis, Antonios Gasteratos, and Ioannis Dokas. 2020. Safety bounds in human robot interaction: A survey. *Safety Science* 127 (July 2020), 104667. https://doi.org/10.1016/j.ssci.2020.104667