Tangible Collaboration: A Human-Centered Approach for Sharing Control With an Actuated-Interface

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ABSTRACT

Autonomous actuated-interfaces provide a unique research opportunity for shared-control interfaces, as the human and the interface collaborate using the physical interaction modality, manipulating the same physical elements at the same time. Prior studies show that sharing control with physical modality interfaces often results in frustration and low sense-of-control. We designed and implemented adaptive behavior for shared-control actuated-interfaces that extends prior work by providing humans the ability to anticipate the autonomous action, and then accept or override it. Results from a controlled study with 24 participants indicate better collaboration in the *Adaptive* condition compared with the *Non-adaptive* one, with improved sense-of-control, feelings of teamwork, and overall collaboration quality. Our work contributes to shared-control tangible, shape-change, and actuated interfaces. We show that leveraging minimal non-verbal social cues to physically communicate the actuated-interface's intent, coupled with providing autonomy to the human to physically accept or override the shift-in-control, improves the shared-control collaboration.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**; **Interactive systems and tools**.

KEYWORDS

Tangible collaboration; Shape change; Actuated interface; Shared-control; Qualitative Methods; Human-centered.

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1 INTRODUCTION

Autonomous actuated-interfaces are physical objects, surfaces, and materials that are controlled using digital computation, introducing novel interactive materials and new interaction paradigms [5, 14, 31, 32, 35, 37, 42]. When a human interacts with an autonomous physical interface, such as an actuated, tangible, or shape-change interface, interaction challenges arise regarding collaboration, coordination, joint action, and shared-control. When a human and an actuated-interface manipulate the same physical elements at the same time, the collaboration process is defined as shared-control [31]. One of the unique aspects of such interfaces is the physical interaction modality that involves autonomous physical gestures. Such gestures are typically interpreted by humans as social cues that form non-verbal communication between the human and the interface [2, 7, 12, 34]. Previous studies have indicated that the human's need for control can impede collaboration, especially when the human is unable to influence the sharing of control and cannot predict when the actuated-interface plans to take control [42]. This collaboration challenge is especially evident in situations of joint action towards a shared goal.

Theoretical works that can inform the design of shared-control autonomous actuated-interfaces include coordination theory, joint intention, joint action, and shared goal.

A framework for coordination theory in the context of HCI was presented by Malone and Crowston's CSCW work [21]. They defined coordination as "the act of managing interdependencies between activities performed to achieve a goal", and listed four components of coordination: Goals, Activities, Actors, and Interdependencies. In the context of one human interacting with a shared-control actuated-interface, we suggest that these terms can be contextualized as follows: Actors are both the human and the

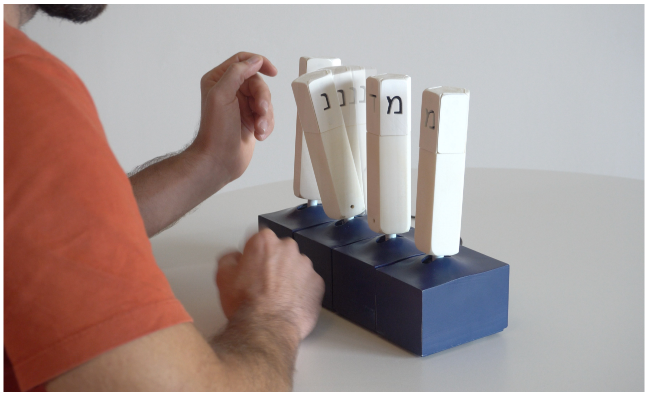

Figure 1: A participant collaborates with the actuated-interface (extended from [43]) using the adaptive collaboration behavior. The actuated-interface performs a signal gesture towards the participant to communicate an attempt to take control, and the participant can choose to maintain or release control by manipulating the pillar or by waiting.

actuated-interface; Goal is the shared goal of both human and actuated-interface; Activities are the actions performed by each actor to achieve the goal; Interdependencies are the interactions between the actions performed by each Actor, which must be managed to achieve coordination, and may result in conflicts between the human's action and the actuated-interface's action. Malone and Crowston acknowledge that conflicts are an inherent aspect of interdependencies, and mixtures of cooperation and conflict are expected and common. One of their recommendations is that system designers manage such interdependencies by establishing a common language based on perception of common objects. In the case of actuated-interfaces, this involves the actuated-interface's ability to identify the human's intent and the human's ability to understand the actuated-interface's intent. Applying these principles may increase the human's ability to anticipate the actuated-interface's action, decrease coordination challenges, increase the human's overall sense of control and improve overall collaboration.

Another relevant perspective is the psychological aspects of human-human coordination, defined by Shteynberg and Galinsky as *implicit coordination* [36]. Implicit coordination focuses on how group members gradually and independently become more attentive and aware of one another's intentions. This connects to Malone and Crowston's recommendations, as the human can gradually become more aware of the system's intention if the system clearly communicates its intention. Shteynberg and Galinsky also define *social tuning* as the gradual change in people's attention towards the communicated attitudes and affective states of other group members. In the context of actuated-interfaces, the human's gradual learning of the actuated-interface's physical communication language and the corresponding changes in the human's actions would be the social tuning. This suggests that designers of shared-control actuated-interfaces should form a human-interface language that uses consistent physical feedback to communicate the actuated-interface's intention to the human, in order to gradually increase the potential to form a common language between the human and the actuated-interface.

Joint intention and *joint action* are additional theoretical perspectives that can further support the design of shared-control interfaces. Cohen et al. define joint intention as the joint commitment to perform an action, and emphasize the agents should "mutually believe" they are committed to do it [6, 19]. Joint action occurs when a group works together and appears to act as a single agent with "intentions of its own" [6]. Levesque et al. further emphasize that joint intention can be achieved by adding signals that allow the confirmation of mutual commitment by the two parties [19]. They explain that signals can be used by the system to better communicate its planned action, and therefore increase the chances for better coordination. They suggest using confirmation signals at the start of the action (for example "Ready"), when there is a transfer of control, and throughout the interaction to support the initial "mutual belief" (as defined by Cohen et al). In the context of actuated-interfaces, such signals can be physical gestures that enhance the non-verbal common language, increasing the human's ability to anticipate the actuated-interface's action.

Another aspect that should be carefully planned in coordination is timing, as detailed by Hoffman in a human-robot interaction context [11]. His work on "fluency of shared activity" emphasizes that precise timing is a key factor to the emergence of coordinated behavior between human and system. This suggests that in the implementation of signals as part of the common language between system and human, the timing and duration of a system's signals can impact the success (or failure) of the coordinated interaction.

Within the actuated interfaces literature, Rasmussen et al. presented a continuum with four types of control: directly controlled, negotiated control, indirectly controlled, and system controlled [31]. Of most relevance for this work is the "negotiated control" type (second in the continuum) which involves a human and an actuated-interface sharing the control, when both can take the control at any time and manipulate the shape-changing interface. Recently, Zuckerman et al. [42] extended Rasmussen's negotiated control type and evaluated two interaction paradigms for actuated-interfaces, asynchronous interaction (defined as *turn-taking-actuation*) and synchronous interaction (defined as *joint-actuation*). Turn-taking-actuation occurs when the human and actuated-interface manipulate the same physical elements, but not at the same time, by taking turns. Joint-actuation occurs when the human and actuated-interface manipulate the same physical elements at the exact same time, as a joint action. In their work, they indicate that in order to design successful collaboration in actuated-interfaces that includes joint-actuation, shared-control conflicts must be addressed. Their findings show participants were very frustrated when the actuated-interface intervened when it wasn't needed (e.g. when the human plans to take action but is still thinking about it), or when the actuated-interface did not intervene when it was needed (e.g. when the human does not know what to do and would appreciate help). Zuckerman et al. concluded that the actuated-interface's inability to adapt to the human's need led participants in both conditions to experience a range of negative emotions including anger, frustration and disappointment from the collaborative process. They explained that participants wanted the interface to understand when they required help and when they did not, allowing them to maintain control or release control based on their need.

In sum, when humans interact with a shared-control actuated-interface the following challenges arise and should be addressed using the physical interaction modality: (A) The human's inability to predict when the actuated-interface will take control and when it will not; (B) The human's inability to reject the actuated-interface's attempt to take control, if the human is still interested in maintaining control; (C) The human's inability to shift the control to the actuated-interface, when the human is interested in releasing control.

We present and evaluate adaptive collaboration behavior for actuated-interfaces, leveraging minimal non-verbal gestures as social cues. Our proposed collaboration behavior has three aspects: (1) The actuated-interface predicts the human's intent to maintain or release control by monitoring the human's physical manipulation using a set of timers; (2) When human intent is detected as "release control", the actuated-interface communicates to the human that it is ready to take control by performing a physical movement that leverages minimal non-verbal social cues (i.e. the signal); (3) The human notices the signal and has the autonomy to release or maintain control by letting the actuated-interface continue with the shift-of-control or by overriding it with a gentle physical manipulation.

We evaluated our adaptive collaboration behavior in a controlled lab study with a working actuated-interface prototype, comparing participants' experience in two conditions: Adaptive and Non-adaptive collaboration behavior. In the study, participants physically collaborated with the autonomous actuated-interface to construct four-letter words together (see Figure 1).

Our main contribution is within the field of actuated, tangible, and shape-changing interfaces:

- Design and implementation of adaptive collaboration behavior with two main principles: (1) Using physical gestures and physical manipulation to establish a common communication language between the human and the actuated-interface, leveraging minimal non-verbal gestures as social cues; (2) A human-centered approach that informs the human about an upcoming shift in control by the actuated-interface, giving the human autonomy to maintain or release control.
- A controlled study comparing the collaborative experience with adaptive behavior vs. non-adaptive behavior, using qualitative analysis to assess collaboration quality, and quantitative analysis to evaluate the effect on participants' perception of the actuated-interface.

2 RELATED WORK

Prior work includes shape-changing and actuated-interfaces that address issues of shared-control, as well as interfaces that do not involve shared-control but leverage force and shape-changing as feedback mechanisms to communicate the system's state to the human. Additional works include human-human collaboration around multi-touch and tabletop interfaces, which demonstrate that design strategies can address conflicts of control.

2.1 Shared-control in collaboration with actuated-interfaces

Conflicts of control between a human and an actuated-interface are evident in the few works that implemented joint-actuation. In such actuated-interfaces, both the human and the system share the control of the same interface at the same time.

In the early work of the PICO prototype [30], the human attempts to optimize a model of cellular network by rearranging physical objects, while the actuated-interface is trying to do the same, at the same time. The human moves an object and the actuated-interface simultaneously moves the rest of the objects, including the object being manipulated by the human. The human senses the actuated-interface's shared-control over the object as physical resistance. In their findings, they report on human frustration due to lack of control during the interaction.

Zuckerman et al. [42] evaluated how people experience two types of interactions with an actuated-interface: turn-taking-actuation and joint-actuation. Their findings show that turn-taking-actuation was experienced as competition, while joint-actuation was experienced as collaboration. In both cases participants sensed a lack of control and asked for "adaptive control", expressing their need to release control only when they need help and not when they are still thinking about their next step.

Within the field of haptic shared-control systems (mostly studied in the context of human-robot collaboration), the most relevant works cover the negotiation of intentions and roles between the human and the system. A recent work by Izadi et al. [15] presents a series of simulation studies that test an algorithm measuring relative force by both the human and the system to identify whether the interaction is cooperative or non-cooperative. Based on the simulation, they suggest that dynamic negotiation of level of control between a human and a system is the most appropriate way to form a capable human-robot team.

2.2 Physical feedback as communication in actuated-interfaces

Physical movement can be used as a feedback mechanism to form a communication language between the system and the human.

The Tangible Active Objects (TAOs) is a furniture layout prototype [33], enabling humans to place furniture elements on an interactive surface. If the human positions a tangible furniture element in an impossible location, the tangible interface generates a vibro-tactile physical feedback in the same item the human is manipulating. Initial explorations revealed that the vibro-tactile feedback was not clear enough as a communication language.

In the Ripple Thermostat prototype [40] force feedback and shape change were explored as feedback modalities, defined as "human-computer dialogue", a communication language between the shape-change system and the human. The thermostat changed shape from "collapsed" to "expanded". The collapsed state was designed to afford standard rotary interaction, and the expanded state was designed to appear more dominant. They found that force feedback affects the experienced dominance while shape-change mainly affects experienced arousal. In another study by the same authors [40], they found that both force feedback and shape change can convey affective meaning.

2.3 Human-human collaboration around multi-touch surfaces and tabletop interfaces

Studies on human-human collaboration around a large multi-user interactive surface or shape-change interface can inform how conflicts of control can be addressed with design strategies.

Hornecker presented the concept of "multiple points of interaction" in tangible tabletop interfaces, showing that providing users with multiple access points can distribute the control in a group of users [13]. Morris et al.'s work on group dynamics around a tabletop interface [26] showed that standard "social protocols of behavior" are not enough to avoid conflicts of control between multiple users, and suggest that designers define explicit multi-user coordination policies to reduce potential conflicts of control.

Lindlbauer et al.'s work on augmenting shape-changing interfaces with graphical representations [20] introduced a design strategy that address the challenge of anticipating when the system is about to initiate an action. They define it as a digital preview, a graphical animation that simulates the expected shape-changing action. The recent KirigamiTable prototype [10] is an actuated shape-changing tabletop furniture prototype that augments the physical shape-changing surface with a visual projection of dynamic content. They demonstrate a design strategy that enables the human to anticipate an upcoming shape-change event, using a slight shape-change action hinting that a full shape-change event is upcoming.

Our work builds on and extends these prior works. We extend the shared-control collaboration approaches presented originally by the PICO project and more recently by Zuckerman et al., by adding adaptive behavior as a solution to the shared-control conflicts. Inspired by the approach suggested by Izadi et al.'s simulation studies we implemented a set of simple timers to sense human intent, and then extended it with human-centered autonomy. We also build on the notion of preview [10, 20] by communicating a physical signal. Finally, we extend all the above by adding human-centered autonomy, in which the human not only anticipates the actuated-interface's action, but can also make a deliberate choice to maintain or release the control to the actuated-interface.

In this paper, we present the design and implementation of adaptive collaboration behavior for actuated-interfaces. We further present a within-participants lab study, in which we evaluate participants' experience and preference when collaborating with the actuated-interface in two conditions, using adaptive and non-adaptive behavior.

3 DESIGN AND IMPLEMENTATION

We used our existing previously-published actuated-interface platform [43], a motor-controlled four-letter anagram interface with four pillars, managed by a software-hardware robotics prototyping platform [23, 24].

The original design team of the actuated-interface included a TUI researcher, a psychologist with expertise in HRI, an industrial designer with expertise in mechanical movement, an animator, robotic engineers, and user-centered design experts. The iterative design process involved continuous testing with users, following two main design guidelines: "authentic appearance" and "social cues as a secondary function" [43].

The "authentic appearance" guideline suggests that the design should not resemble a "fake" living creature like a child or a cat, but clearly represent the main function in an authentic way. The function of a four-letter anagram word task was defined to provide a clear shared goal to which both the participants and the actuated-interface can contribute. As such, the design that represents the main function was defined as a base with four pentagon-shaped pillars. The size of pillars and space between them was defined to allow participants to easily grab and rotate the pillars, and to easily perceive the four letters as one word [43].

The "social cues as a secondary function" guideline suggests that non-verbal communication can form a social experience even when the main function is not defined as a "social companionship". Specifically, "gaze" and "lean" gestures have been shown to increase feelings of friendliness, empathy, and interest [1, 18, 22, 43]. In the existing prototype, each of the four pillars was capable of performing "lean forward", "lean backward", and "gaze" gestures. The "lean" gestures were controlled by one motor that moved each pillar along the vertical axis, and the "gaze" movement was controlled by a different motor that rotated each pillar. The difficulty level of the four-letter anagram task was determined using a predefined time limit and specific sets of letters (verified in a separate online pilot study with 32 participants).

From a technical perspective, the existing prototype already supported joint-actuation, i.e. it was capable of sensing the human's rotation of any of the pillars and identifying a letter position. From an autonomous behavior point of view, the prototype supported word-completion, by sensing the selected letters, searching the word database for words that start with the exact same letters, and then rotating the pillars to complete the selected word.

We extended the existing prototype with new technical implementations that provided the foundations for the adaptive and non-adaptive collaboration behaviors, detailed in the "Technical implementation" section.

3.1 Grounding the design in prior literature

The design of our adaptive collaboration behavior started with concepts presented by prior literature. From coordination theory [21], we adopted the need to establish a common language between the human and the system which contributes to shared intentionality and joint intention [6, 19]. We defined the common language based on non-verbal gestures of the actuated-interface, leveraging the existing physical interaction modality. We adopted the concepts of signal [19] and physical preview [10], enabling participants to anticipate an upcoming change in control when it is initiated by the actuated-interface. To support the human's need for control during the collaboration process [42], we designed the collaboration behavior with human-centered autonomy thus enabling the human to choose if they wish to override the actuated-interface's attempt to take control or to accept it. Inspired by Izadi et al.'s simulations [15], we implemented timers that monitor the human's physical manipulation of the interface thus predicting the human's intent to maintain or release control.

Figure 2: To better understand how to design the non-verbal language between the actuated-interface and the human, we conducted a human-human interaction pilot and asked pairs of participants to construct words together without speaking to each other.

3.2 Pilot study: Insights from human-human collaboration

To further validate our design decisions, we asked 10 participants, divided into pairs, to use the actuated-interface together and to construct as many words as possible while not speaking to each other (see Figure 2). The actuated-interface was not active, i.e. it was not connected to electricity and was only used to support the manual manipulation by participants. We asked participants to collaborate towards the shared goal of constructing four-letter words. Then, we asked them to define a collaboration strategy together. Eventually, we created an imbalance, asking one participant to always start while the other joined during the process. Throughout the pilot participants were communicating using non-verbal gestures. The session was recorded by video for later analysis, with proper consent by participants. Several non-verbal gestures repeated themselves: a pinched hand gesture denoting "wait a second", finger-pointing towards oneself or towards the other to communicate a desired shift in control, pointing to a specific pillar showing "this letter next", head nod in agreement, palms up showing "I have no idea", and spinning their fingers in a circle to communicate "let's start again". The process of forming a common language was clearly observed in the rich informal process of suggesting and interpreting non-verbal communication gestures. The need to anticipate the other party's intention was also evident, as well as the need to request help. This not only supported the need for anticipation, but also supported the design of the human-centered autonomy approach following the communication of the signal.

Following this process and insights, we made the final design choices for the shared-control collaboration behavior. Regarding the gestures, they cannot be mapped directly based on participants' hand gestures, as the actuated-interface morphology is limited to two types of movement: pillar spinning and pillar leaning forward or backwards. The research team observed and classified all of the participants' hand gestures, and sorted them based on frequency of use. The most used gestures were (1) "let's start again" to communicate the need to reset the letters and start another session, and (2) finger-pointing towards oneself or towards the other to communicate a desired shift in control. The research team tested various gesture mappings, considering implementation complexity and previous research regarding human perception of minimal non-verbal social cues when implemented as non-humanoid gestures [2, 7, 12, 34]. The chosen gestures were a 360-degree pillar spin to communicate the "let's start again" (inspired by the finger spinning gesture), and a slow "lean forward" movement by one pillar leaning towards the human to communicate a desired shift in control (inspired by the finger pointing gesture). The "lean forward" gesture was defined as the signal gesture that represents the actuated-interface attempt to shift control. To provide participants the autonomy to decide whether they wish to maintain or release control, the actuated-interface sensed whether participants continued to manipulate the pillars (hence, they wish to maintain control) or refrained from manipulating the pillars (hence, they need help and wish to release control).

3.3 Technical implementation

We extended the original prototype [43] with new technical additions, which are the foundations for the two collaboration behaviors (see Figure 3). We implemented the prediction of human intent using continuous sensing of participants' rotation of the pillars. We tracked several timers to monitor: (1) how long a certain pillar was being rotated; (2) how long the same pillar stopped being rotated; and (3) whether participants rotated a pillar immediately following a signal gesture. These continuous sensing processes enabled us to predict the human's intent to maintain or release control throughout the shared-control collaboration.

The implementation of the timers worked as follows: We defined a human_intent variable that is being continuously updated by the timers to one of two states: intent to maintain control, or intent to release control. The process started with the human_intent variable set to "maintain control". TIMER1 monitored for how long a participant rotated a specific pillar without choosing a letter. From observations of participants interacting with the actuated-interface we saw a clear pattern, that if participants were not able to decide on a specific letter they continued to hold the pillar and slowly rotate it while thinking. We performed 10 short user testing sessions until we observed a pattern that a time duration of five seconds reflected the transition between participant's interest to continue and think about a possible letter vs. their interest to let go and release the

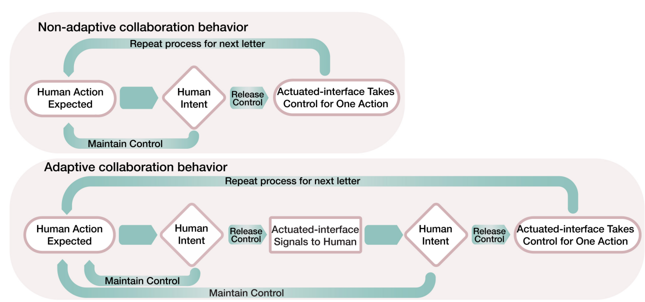

Figure 3: The Adaptive and Non-adaptive collaboration behaviors. The difference in the adaptive behavior is the human-centered autonomy aspect, reflected in the "actuated-interface signals to Human" process and the second human intent condition. In that behavior, if the human intent is "release control" the actuated-interface performs a signal gesture and gives the human another choice to maintain or release control. In the non-adaptive behavior, the actuated-interface takes control immediately after a human intent of "release control", without a signal.

control to the actuated-interface. The rule we implemented was: If TIMER1 ≥ 5 seconds, set the human_intent variable to "release control". TIMER2 monitored the "next letter pillar" after a letter had been selected on a previous pillar, and measured for how long a participant did not rotate a pillar when expected. The relevant pattern we observed in participants' behavior was that if participants did not rotate the next pillar at all (when expected to), they were still thinking about an appropriate letter, and if they did not rotate it for a long enough time, they were ready to release control to the actuated-interface so it could select a letter for them. In an additional set of 10 short user testing sessions, we learned that a time duration of three seconds reflected the transition between "still thinking about a next letter" and "I'd be happy to receive help from the actuated-interface about an appropriate next letter". The rule we implemented was: If TIMER2 ≥ three seconds set the human_intent variable to "release control". TIMER3 only applies to the *Adaptive* condition, and monitors the four seconds following a signal. If TIMER3 < four seconds it means the human has rotated the pillar and therefore human_intent is set to "maintain control". If TIMER3 ≥ four seconds the human_intent is set to "release control". Using these three timers, the actuated-interface continuously monitors the human's activity and determines whether human_intent is "release" or "maintain" (see Figure 3). If the human_intent is "release", the actuated-interface takes control, accesses the word database and selects the next letter in a relevant valid word. If human_intent is "maintain" the actuated-interface does not take control.

In sum, these new technical additions extend prior work and enable the implementation of the adaptive and non-adaptive collaboration behaviors as follows:

3.3.1 Non-adaptive collaboration behavior.

- Start of cycle: At the beginning of the word construction process, all four pillars are set to the "blank" face, so no letter is selected. The participant is expected to take an action by manually rotating the first pillar and selecting an initial letter.
- Measurement of human intent: The timers continuously monitor the human's physical manipulation of the pillars and set the human_intent variable according to the rules detailed above. If the human_intent variable is defined as "release" then the actuated-interface takes control and rotates the pillar autonomously to a valid letter.
- Repeat for all four letters: The process repeats for all four letters, with the actuated-interface expecting a human's action and constantly monitoring the various timers.
- End of cycle: When a four-letter word is completed, the actuated-interface evaluates that word against the word database. If the word is valid and was not assembled before, the actuated-interface will autonomously rotate all pillars to the blank face and restart the process. If the word is incorrect or if it was already assembled (a word the human has already constructed in the current session), the actuated-interface will take control, choose a new valid letter based on the word database, rotate the last pillar by itself, and complete the word to a valid word and restart the process. If no valid letter exists for the current word, the actuated-interface will use a backtracking search algorithm [39] and methodically change the letters until a valid word can be found.

3.3.2 Adaptive collaboration behavior.

- Start of cycle: Same as the previous behavior.
- Measurement of human intent: Same as the previous behavior, with one difference. If the human_intent variable is defined as "release", the actuated-interface starts the signal process.
- Signal process: The signal gesture is performed, followed by another step of measurement of human_intent. If the human_intent is "release" the actuated-interface will take control and autonomously select a letter, in an identical way to the non-adaptive behavior. If human_intent is "maintain", the actuated-interface will not take control and will not select a letter.
- Repeat for all four letters: Same as the previous behavior.
- End of cycle: Same as the previous behavior, with one difference. If the completed word is incorrect or if it's a word that was already assembled, the actuated-interface will not take control but will perform a signal again and again until the human will perform an action and select a different letter that completes a valid word. The actuated-interface will then autonomously rotate all pillars to the blank face and restart the process.

The logic behind the adaptive vs non-adaptive behaviors, the meaning of the signal gesture, and the autonomy participants have to maintain or release control were not explained to participants. We wanted to evaluate whether participants understood the language by themselves during the collaborative experience with the actuated-interface.

4 METHOD

The study was conducted under strict COVID-19 safety regulations. It was reviewed and approved by the ethics committee of the research institute.

4.1 Participants

We recruited 24 young adults to participate in this study (Mean age =25, SD = 3.36; 7 males, 17 females). Participants were BA and MA students at the university, contacted via email and social networks. They were native speakers in the country's language and received extra course credits or a "coffee and pastry" gift card to a local coffee chain.

4.2 Experimental Design

Using a within-participants experimental design we evaluated participants' experience with the shared-control actuated-interface in two conditions: an *Adaptive* condition that includes adaptive control, and a *Non-adaptive* condition that does not include adaptive control (see Figure 4). In both conditions, the actuated-interface could complete the participant's words using the exact same set of letters and exact same word database. In addition, in both conditions the actuated-interface used the same sensing procedure to determine whether a transfer of control is required, based on measurement of human intent (see Technical implementation section).

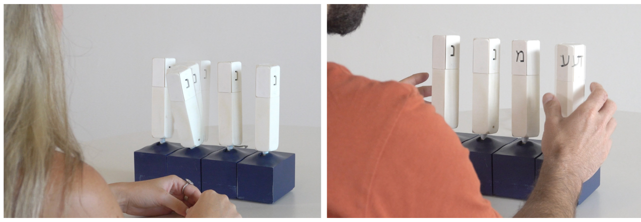

Figure 4: In the *Adaptive* condition (left), the actuated-interface performs a signal before it takes control and the participant has the autonomy to release control or override the actuated-interface's attempt and maintain control. In the *Non-adaptive* condition (right), the actuated-interface takes control immediately. In both conditions, after the actuated-interface takes control it rotates the relevant pillar autonomously to choose a letter.

4.2.1 Non-adaptive condition. In this condition, if the human intent was "release control", the actuated-interface took control, rotated the relevant pillar, and set the next letter in the word based on a valid word from the database. While the actuated-interface rotated the pillar, the participant was not able to stop it. The sensing cycle of human intent would then start again.

4.2.2 Adaptive condition and signal gesture. In this condition, the actuated-interface performed a physical signal (a lean-forward movement by the relevant pillar) if human intent was "release control". Once the signal was performed, the participant was expected to make a choice: maintain control by rotating the relevant pillar or release control by doing nothing and letting the actuated-interface rotate the pillar autonomously. The participant was expected to understand this common language through experience. If the participant rotated the pillar, the sensing cycle of human intent would start again. If the participant released control, the actuated-interface selected the next letter in the word based on a valid word from the database and rotated the relevant pillar accordingly. The sensing cycle of human intent would then start again (see Figure 1).

All participants experienced both conditions. The conditions were counterbalanced to avoid order effects. Half of the participants experienced the *Adaptive* condition first and the other half experienced the *Non-adaptive* condition first. After two experiences, one of each condition, the participants were asked to choose which condition they'd like to experience again during the third phase of the experiment. Each participant experienced one of the conditions again (based on their preference) to increase the validity of their reactions. This grounding of their preference in current actual behavior was required to avoid the influence of the counterbalanced order of the conditions.

In each of the three experiences (first condition, second condition, and a repeated preferred condition) we used a new set of letters (also counterbalanced between participants), to verify that the anagram task was equally challenging across conditions. The number of possible words to be constructed with each set of letters was verified in a separate online pilot study with 32 participants, in which participants wrote as many four-letter words as possible from several sets of letters. Based on that online study, we chose three sets of letters that resulted in a similar amount of words.

4.3 Experimental Settings

The experiment was conducted in a quiet room at the research lab. The room was set to minimize associations to a specific environmental context (i.e. home or work). The actuated-interface was placed on a table, at a fixed location, 15.5 cm from the participant and 64.5 cm from the wall. The participant sat on a chair in front of the actuated-interface. A smartphone and tripod were placed on a fixed shelving unit in the room for documentation via the Zoom platform (see Figure 5).

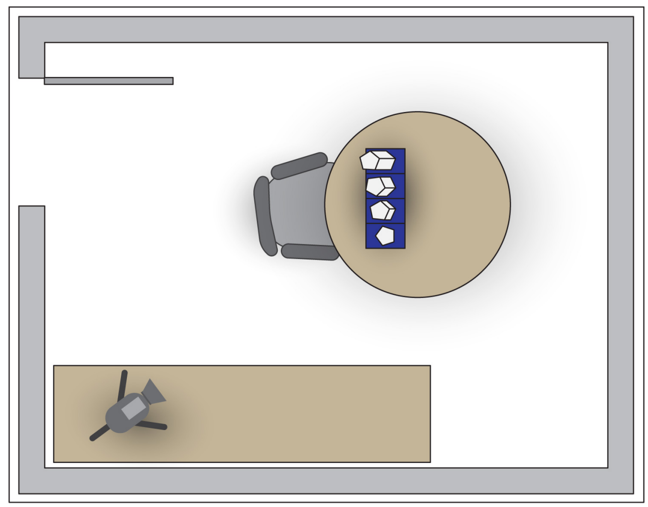

Figure 5: The experimental room included the actuated-interface placed on a table, a chair for the participant that is facing the table, and a shelving unit with a tripod and camera to record the session.

4.4 Measures

We used both qualitative and quantitative measures. The qualitative measures were derived from semi-structured interviews using thematic coding [4, 9]. The quantitative evaluation included the Godspeed questionnaire [3], assessing the Likability, Animacy, and Perceived Intelligence of the actuated-interface.

4.4.1 Semi-structured interview. Semi-structured interviews were used to evaluate participants' experience in the different conditions. The interviews included a short post-experience interview after each condition, and a concluding interview at the end of the study (after the three experiences). In the post-experience interview, participants were asked to describe the current experience. The interview included questions such as, *"Please describe the experience in your own words"; "Please mention positive and negative aspects about the experience"*. The concluding interview was focused on the differences in participants' experience of the two conditions, and included questions such as *"In your own words, how did you feel during each of the experiences?", "How would you describe the main differences between the experiences?", "Can you share why you preferred to redo this experience vs. the other one?"*.

4.4.2 Godspeed questionnaire. Participants' perception of the actuated-interface was evaluated using the Godspeed questionnaire, a five-item Likert scale measure [3]. This assessment allowed us to evaluate the influence of the collaboration model on the actuated-interface Likability (Cronbach's Alpha 0.87), Animacy (Cronbach's Alpha 0.91), and Perceived Intelligence (Cronbach's Alpha 0.83).

4.5 Procedure

When participants arrived at the lab, they signed a consent form and were randomly assigned to one of the counterbalance orders based on their order of arrival. Participants were informed that the room and actuated-interface were sanitized (due to COVID-19 regulations), that the experiment is video and audio recorded, and that they can quit their participation at any time. They were then invited to enter the experimental room. Participants sat in front of the actuated-interface and were provided with a general explanation concerning the activity. The explanation included the activity's goal (to assemble as many four-letter words as possible), how to choose a letter (by rotating the interface's pillars), and that the pillars would rotate back to "blank" when a correct word is found (the pillars' face that has no letters on it). Participants were also informed that the activity involves three short phases (three minutes each) and that at each phase the interface will have a different activity mode. The research assistant (RA) left the room, and based on the counterbalance order, participants began Phase 1 (*Adaptive* or *Non-adaptive* condition). Participants then constructed words with the actuated-interface for three minutes. When Phase 1 was over, the RA returned to the room and the post-experience interview was conducted. After Phase 1, participants were asked to fill in the Godspeed questionnaire outside the experimental room, while the RA changed the letters to a new letter set (the letter set order was also counterbalanced). In Phase 2, participants experienced the other condition (*Adaptive* or *Non-adaptive* based on the counterbalance order). They were asked again to assemble four-letter words with the new set of letters. Participants then interacted with the actuated-interface for another three minutes. As Phase 2 was over, the second post-experience interview was conducted and then participants were asked to leave the room to go fill in a demographic questionnaire while the RA changed the letters to a third set. As participants re-entered the experiment room, they were asked to choose their preferred interaction for the next and final phase. They were given another three minutes to interact with the actuated-interface. After the participants experienced all three phases, the concluding interview was conducted in the experiment room, next to the actuated-interface.

5 ANALYSIS

5.1 Qualitative analysis

The semi-structured interviews were transcribed and analyzed using the thematic coding method [4, 9]. Thematic coding is a qualitative analysis methodology commonly used in HCI for identifying repeating themes in the data. Two independent coders analyzed the data in a process of five stages: (1) Interviews were transcribed and half of the interviews were read several times by two coders to develop a general understanding of the data before the coding process began; (2) Initial themes were identified, presented to a third researcher, and discussed in-depth until inconsistencies were resolved; (3) A list of mutually-agreed themes was defined; (4) The raters used these themes to analyze the second half of the data independently, discussing and resolving any inconsistencies with a third researcher; (5) Inter-rater reliability was verified (Cohen's kappa=84%) and the two coders analyzed the rest of the data.

5.2 Quantitative analysis

The quantitative analysis included a one-way ANOVA comparing the two conditions separately for each of the Godspeed sub-questionnaires (Likability, Animacy, Perceived Intelligence).

6 FINDINGS

6.1 Qualitative findings

In total, 610 quotes were analyzed, leading to four main themes that highlight participants' different interpretations of the collaborative experience in the *Adaptive* vs. *Non-adaptive* conditions. The four themes are: Teamwork quality, Sense of control, Common language between human and actuated-interface, and Purpose of collaboration. In addition, we analyzed the participant's preferred collaboration behavior.

During the study, many participants used the word "he" when relating to the actuated-interface. We note that the word "it" is not a common way to relate to objects in the participants' native language (Hebrew), which may explain the choice of "he".

6.1.1 Theme 1: Teamwork quality. Most participants (18/24) described the interaction with the actuated-interface as teamwork. Their evaluation of the teamwork varied across conditions with mostly positive experiences in the *Adaptive* condition and negative experiences in the *Non-adaptive* condition. Participants elaborated about the teamwork quality, and about the various characteristics of the collaboration.

Adaptive condition. For 14 participants in this condition, the interaction involved equal partners on a team collaborating towards a mutual goal: *"It was like playing with someone and not against someone, we had a common goal and we both did everything we could to reach it"* (P. 16, F). They attributed the quality of the teamwork to the supportive characteristics of the actuated-interface: *"He was with me, supporting and guiding me, helping me reach our goal"* (P. 4, F). Only four participants in the *Adaptive* condition perceived the interaction as an unsuccessful collaboration and even as competition: *"I was trying to think about a word and he interfered, as if he was competing with me"* (P. 15, F).

Non-adaptive condition. In this condition, 12 participants mentioned they were not satisfied with the teamwork quality, emphasizing the lack of collaboration and a negative feeling of not working together: *"He just wouldn't collaborate with me"* (P. 1, F); *"He constantly blocked my attempts to create a word"* (P. 4, F). They explained the actuated-interface disagreed with them and even dismissed their actions: *"It's as if he said, 'No' and canceled what I just did"* (P. 16, F); *"I tried to construct a word and he resisted, as if he was against me"* (P. 23, M). Interestingly, six participants enjoyed the nature of teamwork experienced in the *Non-adaptive* condition, mentioning the challenge and the joy of competition: *"I am a competitive person, so I really enjoyed competing with it, he challenged me"* (P. 6, M).

6.1.2 Theme 2: Sense of control.

Almost all participants discussed the sense of control in the interaction (20/24), however, their experience varied between conditions. While few participants discussed control issues in the *Adaptive* condition, almost all participants discussed sense of control in the *Non-adaptive* condition. In addition, while the *Adaptive* condition led to satisfaction and a strong sense of control, the *Non-adaptive* condition led to frustration and feelings of loss of control.

Adaptive condition. There were eight participants who described a positive experience that involved full control over the task: *"He gave in to me and let me lead the game"* (P. 5, M); *"I was free to do what I want, he just tried to help"* (P. 17, F). They explained that the sense of control was based on the actuated-interface reactions: *"After the signal I could try again, it encouraged me to continue by myself and do better"* (P. 12, F). One participant reported a less positive experience stating that in some cases the actuated-interface took control: *"He sometimes took charge over the task, and decided on the word"* (P. 16, F).

Non-adaptive condition. In this condition, 18 participants discussed their frustration from a low sense of control. They typically mentioned experiencing lack of control due to the actuated-interface taking over the task: *"I didn't control the situation, I couldn't make a final decision, he could always change my words"* (P. 8, F). They were frequently frustrated and upset by the lack of control: *"It was super annoying, I got upset many times during the interaction, it drove me crazy"* (P. 15, F). In some cases they stated that it interfered with their overall performance: *"When it changed my letters it reduced my confidence and made me slow down"* (P. 17, F).

6.1.3 Theme 3: Common language between human and actuated-interface.

A majority of participants (15/24) mentioned different aspects of the communication language with the actuated-interface. They explicitly discussed the non-verbal gestures and stated that the gestures' meaning was to communicate to them relevant information about the activity, or to express the actuated-interface's intent. Participants showed clear preference to the communication language as it was expressed in the *Adaptive* condition.

Adaptive condition. In this condition, 15 participants discussed the actuated-interface's gestures in a positive way, related to the communication as fluent, and felt that understanding the common language contributed to the quality of collaboration: *"I felt that there was a synergy between us, a clear understanding. It assisted in completing the task and constructing words"* (P. 21, F); *"We really communicated, and this way he could tell me that I need to try again"* (P. 4, F). In some cases, they explicitly described the gestures as a non-verbal language: *"It's like trying to communicate with someone who doesn't speak the same language, you use hand gestures to communicate"* (P. 14, F).

Non-adaptive condition. In this condition, eight participants explicitly discussed the language in negative terms. They stated that the actuated-interface communicated with them only when they did not perform well: *"It told me that I was wrong, it wouldn't turn"* (P. 13, M); *"He gave really negative feedback when I was wrong, as if he was angry"* (P. 10, F). Some participants attributed negative social intent to the non-verbal gestures, *"When I was wrong, he was like... I do not feel like playing with you..."* (P. 13, M). In a similar way to the teamwork quality theme, two participants enjoyed the challenging nature of this condition and stated that the negative feedback was helpful: *"Because he gave me negative feedback I understood that I was wrong and could try again. It was helpful"* (P. 9, F).

6.1.4 Theme 4: Purpose of collaboration.

Most participants (15/24) attributed purpose and intent to the actuated-interface, however it differed across the two conditions.

Adaptive condition. In this condition, 13 participants described the actuated-interface's purpose as constructive and positive: *"He was trying to help me, to encourage me to find words"* (P. 14, F). They thought of the actuated-interface as a "supportive guide": *"It's as if someone is sitting next to you, guiding you, asking you to think about additional options"* (P. 16, F). They emphasized that its purpose was to motivate and encourage them: *"He was supportive, as if he was saying - you are really close, let's see what is missing"* (P. 12, F). Only two participants in this condition did not feel the actuated-interface was helpful: *"Our task was to construct words but he didn't help at all. He did not tell me if we are right or wrong"* (P. 6, M).

Non-adaptive condition. In this condition, nine participants also referred to the actuated-interface's purpose as teacher or guide, but as a "challenging guide" more than a "supportive guide", describing it as an intelligent teacher who is trying to improve their skills: *"He wanted to teach me new words, to build my skills, giving me ideas for words that I didn't consider"* (P. 7, M). A few participants explained that its purpose was not to support them but to challenge them: *"He made the task more complicated, creating a challenging experience"* (P. 11, M).

6.1.5 Participant's preferred collaboration behavior.

When participants were asked directly about their preferred collaboration behavior, most participants (17/24) chose the adaptive behavior. When asked why, they attributed their preference to their sense of control in the interaction: *"I was in complete control and no one interfered with what I was doing"* (P. 23, M); to the constructive communication with the actuated-interface: *"There was greater communication between us, a richer interaction, he gave me feedback that I could use in order to perform better"* (P. 4, F); and to the actuated-interface's characteristics: *"He was more friendly, nicer"* (P. 1, F). The few participants who preferred the non-adaptive behavior (6/24) attributed their preference to the challenge it added to the interaction: *"It was more challenging so it made it more interesting"* (P. 13, M); or to the greater efficiency: *"It was completing my words by itself, helping me construct more words"* (P. 9, F); *"It wasn't moving forward and backwards so it was less distracting"* (P. 18, F).

6.2 Quantitative findings: Godspeed questionnaire

Using a one-way ANOVA we compared participants' perception of the object on three of the Godspeed subscales: Likability, Animacy, and Perceived Intelligence. The analysis revealed that the type of collaboration behavior (adaptive vs. non-adaptive) influenced only the object's Likability, $F(1,22) = 4.75, P=0.04$. The *Adaptive* condition resulted in higher Likability ratings than the *Non-adaptive* condition (see Figure 6). There was no significant difference between conditions in the Animacy and Perceived Intelligence ratings (see Table 1).

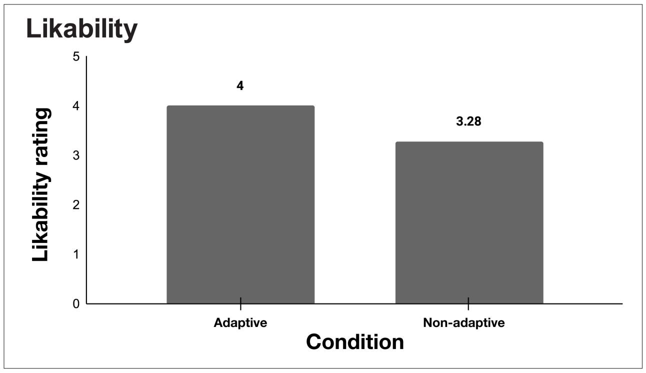

Figure 6: Higher Likability ratings in the *Adaptive* condition in comparison to the *Non-adaptive* condition.

Table 1: Averages and standard deviations of the Godspeed sub-scales per condition.

	Adaptive Average (SD)	Non-Adaptive Average (SD)
Likability	4.00(0.5)	3.28(0.6)
Animacy	3.71(0.9)	3.59(0.8)
Perceived Intelligence	3.83(0.7)	3.75(0.9)

7 DISCUSSION

In this work, we presented and validated an adaptive shared-control collaboration behavior for actuated-interfaces. Compared with a *Non-adaptive* condition, the *Adaptive* condition led to improved teamwork quality, better sense-of-control, and more positive perception of the shared-control experience overall.

We implemented the adaptive collaboration behavior according to three principles: (1) Communication language: we leveraged the natural physical interaction modality of an actuated-interface, and designed minimal non-verbal gestures as social cues to communicate the interface's intent to the human, mainly a "lean forward" signal that communicates the actuated interface's upcoming shift in control; (2) Human intent: we implemented a set of simple timers that continuously monitor the human's physical manipulation of the interface, measuring duration of inactivity at specific stages of the interaction, to predict two types of intent: "participant is still thinking about next step and is interested to maintain control" vs. "participant needs help and is interested to release control"; (3) Human-centered autonomy: we implemented a process that provides participants the autonomy to maintain control (by continuing to physically manipulate the pillars) or to release control (by not manipulating any of the pillars). To validate our proposed collaboration behavior, we compared participants' experience in *Adaptive* and *Non-adaptive* collaboration conditions, using an anagram task that involves shared-control collaboration towards a joint goal: constructing as many four-letter words as possible in three minutes. The main difference in the *Adaptive* condition was the human-centered collaboration behavior detailed above.

Our findings indicate that participants have a clear preference towards the *Adaptive* condition, that their preference is expressed in several ways:

- First, most participants perceived the interaction in the *Adaptive* condition as a positive collaborative experience where they and the actuated-interface worked together towards reaching a mutual goal. They considered the interaction as high quality teamwork that empowers them and increases their chances to reach the desired goal. They described the actuated-interface as a "supportive guide", and they interpreted the shared-control events as the interface's attempt to motivate them and encourage them. Participants consistently used terms such as *encouraging, supportive,* and *motivating*. They explained that the actuated-interface was *with them, helping them, and collaborating with them.* In comparison, in the *Non-adaptive* condition most participants perceived the interaction as a negative experience, expressing lack of collaboration or teamwork, feeling the actuated-interface dismissed their actions and disagreed with them. Participants described the experience in the *Non-adaptive* condition as *annoying, interrupting, and frustrating*, and explained that the actuated-interface was *working against them, resisting them, and competing against them.*
- Second, in the *Adaptive* condition, participants did not experience the known problems related to frustration and low sense-of-control, as indicated by previous studies [31, 42]. They felt that they were leading the interaction, leading the shared activity, and that they were free to make any choice they found appropriate during the shared-control process. In contrast, in the *Non-adaptive* condition, most participants reported a need to struggle for control and feeling helpless. They were upset by the lack of control, and felt it interfered with their performance.
- Third, in the *Adaptive* condition participants experienced the communication with the actuated-interface as rich and fluent communication language, although it was very minimal and limited to physical non-verbal communication only. They attributed the positive experience to the "clear and supportive" common language with the actuated-interface. In contrast, in the *Non-adaptive* condition, most participants did not refer to the interaction as a language. The few that did discuss the communication with the actuated-interface described it as a negative experience highlighting their own errors.

A few participants preferred the *Non-adaptive* condition, explaining that it challenged them by making the task harder, and mentioned a "joy of competition". Unlike most participants, their interpretation of the actuated-interface was a "challenging guide" not a "supportive guide". Some of those participants attributed this preference to their own competitive personality. This preference was minimal, but may suggest a direction for future studies, about the possible individual differences in preference of collaboration behavior among participants with more competitive personalities. Another possible explanation to these individual differences can resonate with Nass et al.'s seminal 1996 paper about teamwork with a computer display [27]. In our work, participants in the *Adaptive* condition reported an increase in feelings of being on a team with the actuated interface, and felt they had a common language with it. According to Nass et al., these participants' preference may indicate they are more likely to conform to the actuated interface's suggestions. Such individual differences should be further explored in future work.

Our findings can also be interpreted in light of the emerging field of Graspable AI presented by Ghajargar et al.'s 2021 paper [8]. They discuss the potential advantages tangible interfaces can bring to the evolving field of explainable AI, by extending explainable AI beyond the visual and audible interaction modalities to the physical interaction modality. They discuss the idea that prediction models may be better understood and perceived if people could hold or grasp them with their hands. The authors suggest exploring familiar metaphors as ways to help people explore prediction models with their hands, in the hope to increase perception of control, trust, and provide opportunities for people to correct a system's shortcomings. Our work provides empirical support to Ghajargar et al.'s suggested approach, by showing that communicating the state of a prediction model using the physical interaction modality (i.e. communicating a signal using physical movement leveraging human perception of minimal non-verbal gestures as social cues) and providing autonomy to override the actuated-interface's shortcomings (i.e. enabling participants to override the interface's attempt to shift control) leads to improved teamwork quality, better sense-of-control, and more positive feelings about the shared-control experience overall.

More broadly, our work can contribute to applications that leverage the physical interaction modality and involve shared-control between the human and the interface. One relevant application domain is future autonomous cooking machines. Some researchers propose fully autonomous machines with no human interaction [17, 41], while others promote a more human-machine collaborative approach in the future kitchen [25, 38]. Our guidelines for human-centered adaptive collaboration can inspire such future work on autonomous machines that cut, peel, stir, mix, and knead, but unlike existing machines, they may support shared-control collaboration, letting the human cook feel in control throughout the collaboration process, intervene when needed, while allowing the cooking machine to perform autonomous functions when appropriate. Another relevant application domain is human-robot collaboration in manufacturing. Researchers describe the challenge of a human holding a robotic arm and hand-guiding the arm, leveraging the human's ability to guide and the robot's ability to force-lift [16]. A human-centered adaptive collaboration behavior adapted from our work and tailored to the specific system and context-of-use, that leverages our suggested guidelines (forming a common language, predicting human's intent, and enabling human-centered autonomy in the interaction), may lead to better teamwork quality and improved sense-of-control in the human-robot collaboration.

Clearly, our proposed human-centered collaboration behavior is not appropriate for every collaboration with a tangible interface or a robot. For example, in time-sensitive interfaces that may be involved in emergency situations, our proposed human-centered autonomy is inappropriate. If the interface is expected to communicate its attempt to the human and then wait for the human's reaction before actually taking control, it will slow down the shift in control and will fail to act in an emergency situation. However, in shared-control collaboration that is not time-sensitive, specifically in cases where the human's sense of control and feeling of positive teamwork is important, our proposed collaboration behavior is appropriate. In addition, we did not address all possible conflicts but focused on the main ones, for example we did not address the challenge of overriding after the motors have already started to move. Future work should further implement such cases.

We present the following insights for designers of shared control interfaces that are based on physical interaction, and specifically for designers of actuated-interfaces:

- Establishing a common language: coordination theory informs us that a common language is essential for successful collaboration [21]. The minimal non-verbal gestures we implemented were not explained to participants, and they perceived it as a common language in a gradual process throughout the collaboration activity with the actuated-interface. We designed the gestures based on pilot studies of human-human interaction, and based on theory of minimal non-verbal gestures as social cues. We performed validation studies to verify the gestures can be understood in the context of the task. Our findings indicate that the minimal non-verbal gestures were effective in communicating the actuated-interface's intent, leveraging the physical interaction modality instead of adding additional mediums of communication.
- "Good enough" prediction of intent: we continuously monitored the human's behavior in an effort to predict whether the human's intent is to maintain control or release control. This is of course domain-specific, and the relevant implementation of sensing technology will be different in different contexts. In our case, we used a simple time measurement of the human's physical manipulation or lack of manipulation as a prediction of human intent. Our prediction was not perfect, however, we provided an ability for the human to overcome false prediction by simply overriding the actuated-interface's decision to take control (see the third design recommendation).
- Striving for human-centered autonomy: sense-of-control is a critical aspect in shared-control actuated-interfaces. We recommend designing for human autonomy throughout the shared-control process, by providing humans the ability to maintain or release control as they desire. The actuated-interface communicated to the human when it is ready to take control (using the physical signal), and provided participants the autonomy to choose if they want to accept the shift in control or override it.

8 LIMITATIONS

This study has several limitations. First, qualitative interviews may be biased by the interviewers' thoughts and expectations [29]. We minimized this risk by following a detailed protocol and increasing the interviewers' awareness of their verbal and non-verbal reactions during each interview. Interviews may also be biased by the "good subject effect" [28] and participants' willingness to provide pleasing answers. To minimize this limitation, we explained to the participants that there are no correct answers and that all answers are helpful. In addition, all participants experienced both conditions and did not know which one will "please" the interviewer.

Indeed, the interview findings indicate a range of both positive and negative comments for each condition. Furthermore, as in every within-participants experimental design, the result may be biased by an order effect. To deal with this, we counterbalanced the conditions and verified that there was no interaction between the counterbalance and the collaboration behavior conditions. Another limitation concerns the specific context (anagram task) and length of the interaction. It is possible that a different context would lead to a different experience and different preference of shared-control behavior.

9 CONCLUSION

In sum, our work indicates that adaptive collaboration behavior is a promising direction for improved teamwork between a human and an autonomous actuated-interface. The known frustrations and feelings of lack of control that humans feel when interacting with autonomous actuated-interfaces can be addressed by establishing a supportive common language between the human and the actuated-interface, and by providing human-centered autonomy throughout the collaboration process.

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