TUI as Social Entity: a Study of Joint-actuation and Turn-taking-actuation in Actuated-interfaces

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ABSTRACT

We present an actuated-interface that is not only a tangible interface but also an autonomous object, designed as an independent entity that takes a similar role to the user's role in an anagram word game. We highlight two leading interaction paradigms: Turn-taking-actuation and Joint-actuation, and evaluate both in a qualitative interaction study with the autonomous actuated-interface. Our findings reveal that all participants perceived the interaction as a social experience. The different interaction paradigms led to different interpretations: Turn-taking-actuation was interpreted as a competitive experience, while Joint-actuation was interpreted as a collaborative experience. The interaction paradigms also influenced the intensity of emotions and perception of control, with Joint-actuation leading to more intense emotions and higher sensitivity to control in the interaction. To conclude, our findings show that it is possible to design an actuated-interface that users perceive both as a tangible interface and as a social entity with its own intent.

CCS CONCEPTS

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

KEYWORDS

TUI; actuated-interface; self-actuation; autonomous behavior; social interaction

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Figure 1: The actuated-interface (extended from [44]), designed as an anagram game with four pillars, each with four Hebrew letters, for both user and system to construct words.

1 INTRODUCTION

The field of Tangible-User-Interface (TUI) has been instrumental in the evolution of Human-computer Interaction (HCI) with physical interfaces. In 1995, Fitzmaurice, Ishii, and Buxton's introduced *"Graspable-user Interfaces"*, defined as *"direct control of electronic or virtual objects through physical handles for control"* [11]. Ishii & Ullmer's influential 1997 vision of tangible bits defined TUI as *"a new type of HCI, coupling digital information to everyday physical objects and environments"* [14]. A lot of work has been done following these early pioneers (e.g. [3, 10, 15]), among them are Shaer & Hornecker who clarified the definition of TUI as the coupling between input and output when the input is a *"tangible manipulation"* by the user and the output is a *"tangible representation"* by the system [36].

Researchers within the TUI domain have been exploring the integration of autonomous processes into tangible interfaces, leading to autonomous TUI behavior, manifested in the emerging fields of actuated-interfaces [27, 28, 30] and shape-changing interfaces [8, 39]. Unlike the classic TUI definition in which the user performs an action of manipulation and the system reacts with a feedback of tangible representation, autonomous tangible prototypes can also perform the action of manipulation, instead or in parallel to the user's action.

An early conceptual work of autonomous TUI behavior was introduced in 1965 in Sutherland's vision of "The Ultimate Display" [40], presenting a concept for a "Kinesthetic Display" that changes its physical appearance autonomously. In 1996, Shieber introduced the notion of Collaborative Interfaces, where the human and interface work together towards a common goal as true collaborators, with the interface initiating its own autonomous actions [37]. From an interaction paradigms perspective, Beaudouin-Lafon introduced the classification of computer-as-tool paradigm (extending human abilities through a tool) and computer-as-partner paradigm (anthropomorphic means of communication including agent-based interaction), and called for researchers to design interaction paradigms that integrate both [5].

In the recent two decades, researchers implemented a range of systems that integrate autonomous behavior into TUIs, using different terms and interaction paradigms. These paradigms include either an asynchronous interaction where the user and system perform actions in turns, or synchronous interaction where the user and system perform actions at the same time.

In 2002, Pangaro et al. [27] presented the Actuated Workbench, an early prototype of autonomous actuation with several asynchronous use-cases. In 2004, Rosenfeld et al. presented Bi-directional User Interfaces and the *"Tangible Elements"* perspective, with the user and system taking turns when performing actions on tangible elements [34]. In 2007, Poupyrev et al. introduced the notion of actuated-interfaces, and the term self-actuation (i.e. the system's autonomous actuation) [30]. These works represent an asynchronous "turn-taking" interaction in which the user and the system manipulate the same tangible elements, but not at the same time. In the same year Patten and Ishii extended self-actuation beyond asynchronous turn-taking, using the PICO system [28]. In PICO the user can physically hold one of the tangible elements, and the system not only moves the other elements, but can also apply force to the same element the user is holding, which is experienced by the user as physical resistance to her own action. This presents synchronous interaction, a "joint-action" that is performed both by the user and the system simultaneously, actuating the same tangible element at the exact same time.

Shape-changing interfaces are another form of actuated-interfaces. An early conceptual work in shape-changing interfaces was presented in 2011 by Coelho & Zigelbaum [8] who presented a variety of prototypes with both asynchronous and synchronous actuation including force-feedback and counteracting the user's deformation. Since 2011 more advanced shape-changing prototypes have been created, exploring both asynchronous "turn-taking" and synchronous "joint-action" interactions. Recompose [6] and later inFORM [12] demonstrated interaction at scale with hundreds of tangible elements (pins). Riedenklau et al. presented synchronous autonomous processes in TUIs with the system applying vibrations to provide feedback to the user's physical action [33]. Nowacka and Kirk introduced tangibles with simple autonomous processes that give users the impression of having an internal state, demonstrating higher levels of autonomy [25].

The asynchronous and synchronous interaction paradigms presented above can be contextualized within Rasmussen's framework of "shared control" for shape-changing interfaces [32], that introduced a continuum with four types of control: directly controlled, negotiated control, indirectly controlled, and system controlled. The "negotiated control" type involves sharing the control, enabling both the user and the system to take the initiative and perform a shape-change. We define the asynchronous interaction as "Turn-taking-actuation" and the synchronous interaction as "Joint-actuation" interaction paradigms, and contextualize them as two forms of "negotiated control", where the system and the user have to negotiate the control over the shape-changing or actuated interface.

1.1 Turn-taking-actuation: asynchronous "negotiated control"

In this interaction paradigm the autonomous actuated-interface and the user take turns in manipulating the same tangible interface element in an asynchronous way. The user and system are taking turns, manipulating the same tangible interface element but not at the same time. For example, the user is grasping and moving/manipulating objects, then releasing the objects, and the system takes control and moves/manipulates the exact same objects [27, 30, 34].

1.2 Joint-actuation: synchronous "negotiated control"

In this interaction paradigm the autonomous actuated-interface and the user manipulate the exact same tangible interface element at the same time (e.g. in a synchronous way). For example, the user is grasping and moving/manipulating objects, while the system is also moving/manipulating the exact same objects at the same time. This requires the user to quickly adapt to the system's manipulation and to "negotiate the control" over the interface. This paradigm presents a greater challenge to a user's sense of control [12, 28, 33].

Autonomous processes were also explored in a Human-Robot Interaction (HRI) context. These studies commonly evaluate a human interacting with an autonomous robot. Studies showed such interactions are perceived by participants as a social experience, even with non-humanoid abstract robots that perform minimal movements [2, 9, 16, 38]. In contrast to TUI and actuated-interfaces, these human-robot interaction studies do not involve direct tangible manipulation. The few HRI studies that include physical manipulation of an interface use a non-actuated interface, one that is manipulated by two separate entities: a user and a robot [18], the interface itself is never acting autonomously.

Unlike prior work in HRI, in which the social entity is a robot that manipulates the interface as an independent entity, we present a system in which the actuated-interface is both the interface and the autonomous entity manipulating the interface.

In this work we present a working prototype of an actuated-interface that is not only a TUI but also an autonomous entity. We evaluate if the interface itself can be perceived as a social entity, and specifically if the negotiated control between the user's manipulation of the interface and the interface's autonomy does not compromise the social interpretation. We present a prototype designed as a tangible word game, enabling both the user and the system to construct words using the exact same tangible elements, in two conditions: Turn-taking-actuation, in which the user and system take turns when constructing words, and Joint-actuation, in which the user and system construct words at the same time. To implement the system, we extended our previously published robotic object platform [44] (See Figure 1) with autonomous processes, and implemented the two interaction paradigms. We report on a lab study in which we compared how participants interpret each of the two paradigms, evaluating if they perceive the interaction as a social experience in a similar way to HRI works, or as an interaction with a system, in a similar way to TUIs.

2 RELATED WORK

We review shape-changing studies that evaluated the interactive experience, actuated and shape-changing interfaces that implemented Turn-taking-actuation or Joint-actuation interaction paradigms, and HRI studies that include a physical interface.

2.1 Studies of interaction paradigms in shape-changing interfaces

In recent years, key studies have been published evaluating the interactive experience with shape-changing interfaces. Pedersen et al. [29] performed a comprehensive video study evaluating how people perceive varying shape-change parameters of a handheld device. The degree of shape change was found to impact the experience more than the type of shape change. Tan et al. [42] evaluated how six movement behaviors are perceived along Ekman's emotion scale, offering an initial basis for the systematic design of emotions in shape-changing interfaces. Tiab et al. [43] studied interaction with various mechanisms for shape-changing buttons, reporting on users' perception of affordance, system state, and feedback. Kim et al. [17] explored the design space of the KnobSlider shape-changing physical prototype, evaluating participants' subjective preference of speed, suggesting speed-related design guidelines for shape-changing interfaces.

These studies are instrumental to the increased body of knowledge concerning design aspects of shape-changing interfaces. Our work differs by comparing two specific interaction paradigms using a physical autonomous prototype, and by exploring the notion of the interface as a social entity.

2.2 Prototypes with Turn-taking-actuation interaction paradigm

Pangaro et al. [27] presented the Actuated Workbench, a pioneering tabletop prototype of an actuated interface, able to move physical magnetic "pucks" over an array of electromagnets. In their paper they describe possible applications, mostly using the Turn-taking-actuation interaction paradigm, for example a tangible simulation of a solar system in which the user can teach the system a new orbit path and then watch the resulting motions of the planets.

Another tabletop based Turn-taking-actuation was demonstrated by The Planar Manipulator Display prototype [34], that enables movement of small furniture items in a model of a room. Users place furniture items in a desired location, then the system moves the rest of the furniture according to a user-selected layout.

Another category of Turn-taking-actuation prototypes goes beyond tabletop interfaces and involves physical devices. Reactile [41] is a swarm-robots prototype designed to simplify swarm programming, the user physically moves one or more markers, and the system responds by adjusting the rest of the markers based on predetermined mapping. Morphees [35] is a shape-changing mobile prototype that can adapt its shape, for example curl inward to enhance typing. The user initiates an action and the prototype responds with a shape-change. The Aerial tunes [1] prototype allows users to manipulate the height of a hovering ball, and the air blower intensity is adjusted to maintain the ball's height.

Informal user studies of the above-mentioned prototypes showed Turn-taking-actuation is helpful, can increase curiosity, and is perceived as a fun and engaging interaction.

2.3 Prototypes with Joint-actuation interaction paradigm

Prototypes that implement Joint-actuation also support Turn-taking-actuation. One of the earliest examples of Joint-actuation is Pico [28], a tabletop interface that can sense and move small disc-like objects. The user, together with the system, attempts to optimize a model of cellular network by rearranging physical objects on the tabletop. When the user moves one of the objects, the system continuously moves the rest of the objects to optimize the layout, including the object the user is currently manipulating (the user feels it as physical resistance). In the evaluation study of Pico, users showed increased performance and reported on easier and quicker exploration. Users also reported on frustration due to the lack of control they were experiencing during the interaction.

Another prototype that implemented Joint-actuation using vibrations as feedback is the Tangible Active Objects (TAOs) [33], a furniture layout system that provides synchronous tactile feedback (vibration) as users manipulate the system's furniture elements. When users place a tangible furniture element in an impossible location, the system reacts with a synchronous vibration feedback in the same tangible element the user is holding.

Joint-actuation on a large tabletop interface was presented by inForm, an advanced 2.5D shape-changing display [12] that supports both Turn-taking-actuation and Joint-actuation. For example, the system can display a physical representation of a car model, and the user can manipulate the interface to fine-tune the design (Turn-taking-actuation), or physically resist the actuation by holding pins in one position (Joint-actuation). Informal qualitative feedback showed that users appreciated the "on demand" transformation of physical user-interface elements, and expressed delight with the autonomous movement of objects on the table.

Joint-actuation using chains of tangible elements was demonstrated using the LineFORM prototype [23], a line of actuated elements that can change shape into a curve or 2D shapes. A user can record specific body movements as constraints and the system then imposes the same constraints in following uses (Turn-take-actuation). LineFORM also provides real time haptic feedback to the user's manipulation, with varying levels of stiffness, that guide and direct the user's deformation of its shape (Joint-actuation).

In sum, Turn-taking-actuation and Joint-actuation have been previously implemented in various works, but have not been compared and evaluated as two different interaction paradigms, in the context of shared control between the user and the system.

2.4 HRI: Non-humanoid Robots and Tangible Manipulation

HRI works that are relevant for this paper concern human-robot interaction studies that include a user, a robot, and a physical interface (e.g. tangible manipulation).

Law et al. (2019) introduced a human-robot collaborative design task [18], involving the human user, a robotic arm, and passive physical interface elements. Both the human and the robot can manipulate the same non-actuated interface elements, with a shared goal to reach an optimal configuration of Earth-Observing Satellites. Some users took turns with the robot, waiting for the robot to complete its action before performing their own, while other users worked simultaneously with the robot and manipulated objects at the same time as the robot. Findings from the qualitative user study showed that users assigned social roles to the robot and to themselves, using words such as subordinate, leader, colleague, and adversary. Users also attributed agency to the robot, reported emotional reactions, were frustrated when they thought the robot ignored them, and felt content when they thought the robot was listening to them [18].

Another example for a non-humanoid robot design that involves some tangible interaction was presented by Luria et al. [19]. The robot was designed as an assistant for smart home management, with a set of non-actuated physical elements, each representing a smart home device. When the user placed a specific physical element at the robot's base, the robot identified that object using computer vision. Then, the robot performed a relevant social gesture as feedback to the user (e.g. bowing, seeking attention).

In both of these projects the interaction with the autonomous non-humanoid robot led to a social and even emotional experience. However, none of these projects involves tangible manipulation by both the user and the robot. Actuated-interfaces present a special case that is inherently different from a human-robot-interface interaction, since a single device serves both as the tangible interface and the autonomous entity.

In sum, the field of actuated-interfaces is very relevant to evaluate research questions concerning physical interaction with autonomous processes, and the possible social interpretations people may attribute to such interactions. We present a physical interaction study with an actuated-interface, designed to take a role in the interaction that is similar to the user's role (construct words in an anagram game). We report on insights from a qualitative user evaluation, analysing participants' interpretations and perception of control with both Turn-taking-actuation and Joint-actuation interaction paradigms.

Figure 2: A participant rotating one of the pillars to select a letter and construct a 3-letter word (last pillar is a "blank letter" in this case).

3 TECHNICAL IMPLEMENTATION

The system is a physical device with four motor-controlled pillars that can also be manipulated by participants (see Figure 2). The device is designed as an Anagram game, enabling the user and the system to construct 4-letter words by rotating the pillars (See the Procedure section for elaboration about the anagram game). To create the system, we used our previously published robotic object platform [44] and extended it with autonomous word-completion, accurate sensing of letter selection by participants, and simple game mechanics of an Anagram word game. These technical additions enable implementation of the two interaction paradigms which are the subject of this work. In the Turn-taking-actuation paradigm the user and system are constructing words in alternating turns. In the Joint-actuation paradigm, the user and system are both choosing letters and constructing words at the same time, with the system performing word-completion for the user, leveraging the autonomous process that controls the motors.

3.1 Hardware

The system's infrastructure includes a Raspberry Pi shield and Dynamixel smart servo motors that enables motor control and position reading (which is essential for letter sensing during tangible manipulation). The hardware-software control is handled using the "Butter" robotics prototyping platform [20, 21], designed as an abstraction layer that simplifies control of the motors. Each pillar is controlled by two motors: a horizontal turn-motor (MX-12W) and a vertical lean-motor (MX-28).

The system has several software modules, written in Python and Javascript, managed by a 'Flask' server. The *Experiment Handler* is the main loop of the experiment and game mechanics, it manages timers, experiment phases (monitor desired length of word), experiment logs, and Word Database queries that compare each detected word to a list of valid words. The *Motor-letter handler* senses the user letter-selection by constantly querying the turn-motors for their positions (4096 degrees for a full circle), when a motor position is read, the controller is able to map the given degree to

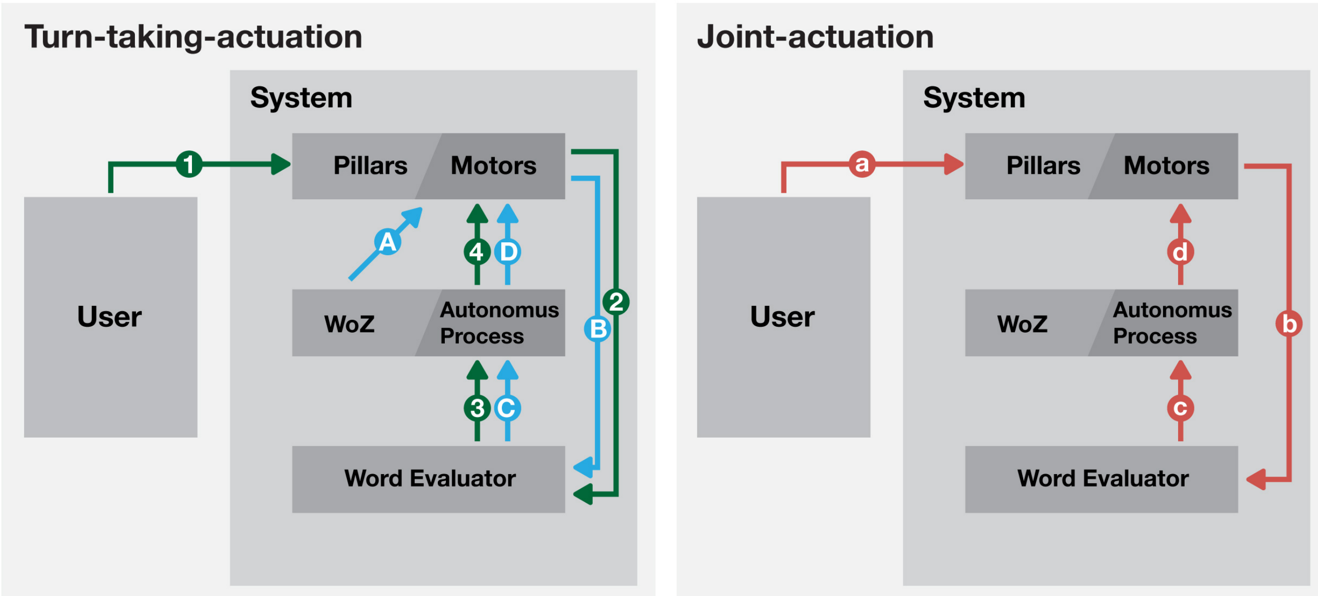

Figure 3: The Turn-taking-actuation implementation (left): user (green, 1-4) and system (blue, A-D) take turns. In the user's turn (1), the user is manipulating the pillars by hand; In the system's turn (A), the researcher selects letters using the WoZ interface that controls the motor controller which manipulates the pillars. In both turns, the letter sensing (2, B) senses the letters, the word evaluator (3, C) verifies it's a valid word, and the autonomous process (4, D) provides feedback. The Joint-actuation implementation (right): both user and system can manipulate the pillars (a, d); The user starts (a), then the letter sensing senses the letters (b), the word evaluator verifies it's a valid word (c), and the autonomous process is ready to complete the word and provide feedback (d).

the corresponding letter. The read letters are concatenated into a string, which is sent to the experiment handler for comparison in the words database. The *Autonomous Word-Completion Controller* is triggered when the composed word is of length n-1 (according to the current experiment phase, 2-letter, 3-letter, or 4-letter phases). If the controller locates a valid word in the word database, it calls the motor-letter handler to operate the motors and set the last letter that completes the word. The *Wizard-of-Oz (WoZ) controller* is an interface for the researcher to control the study overall process, including manual control of letters when needed. WoZ is a common method when evaluating the effects of autonomous processes of actuated-interfaces (e.g. [22, 31]). In the Turn-taking-actuation paradigm the WoZ is used when it's the system's turn to construct a word. A random word is selected from the same database used in the Joint-actuation paradigm. The WoZ operator is typing those letters into the WoZ interface, which sends the relevant commands to the motors, and the autonomous motor-letter handler senses the letters in the same way it does during a user's turn.

3.2 Interaction Paradigms Implementation

The Turn-taking-actuation interaction paradigm starts with a user's turn, then continues with word completion through the WoZ controller, then back to the user's turn (see Figure 3, on the left). In the Joint-actuation interaction paradigm the user initiates each interaction and tries to complete a word. If the system identifies no movement for more than 0.3 second in pillar n-1 (when n is word length based on difficulty level) the autonomous Word Completion Controller is triggered and the word is completed by the system (see Figure 3, on the right).

4 METHOD

The study was conducted under strict COVID-19 safety regulations that were reviewed and approved by the ethics committee of the research institute. The actuated-interface and the experimental room were sanitized after each experiment, and the interview was conducted while keeping safe distance and wearing masks.

4.1 Participants

23 young adults participated in this study (M = 28.9, SD = 7.7; 13 males, 10 females). All participants were native speakers in Hebrew (the language in which the research was conducted). All participants signed an informed consent form, and received extra course credits or a "coffee and pastry" gift card to a local coffee chain.

4.2 Experimental Design

We conducted a within-participants study to evaluate participants' experience when interacting with the actuated-interface. We compared participants' experience in the two interaction paradigms: Turn-taking-actuation and Joint-actuation. All participants experienced both interaction paradigms using the same actuated-interface. The conditions (interaction paradigms) were counterbalanced to

Table 1: Counter balanced condition: four variations of interaction with the actuated-interface.

Variation	Conditions Order	Letter set
1	Turn-taking-actuation, Joint-actuation	A
2	Turn-taking-actuation, Joint-actuation	B
3	Joint-actuation, Turn-taking-actuation	A
4	Joint-actuation, Turn-taking-actuation	B

avoid order effects. Half of the participants experienced Turn-taking-actuation interaction first and the other half experienced the Joint-actuation interaction first. We used two different sets of four-letters (also counterbalanced between conditions), so that participants received different letter sets in the different interaction paradigms (see Table 1). The two sets of letters were chosen based on a pilot study with 10 participants that were asked to write as many words as possible from several sets of letters. We chose two sets of letters that resulted in a similar amount of words.

4.2.1 Turn-taking-actuation Condition. In the Turn-taking-actuation condition the participants took turns with the actuated-interface. After a participant constructed a correct word, the actuated-interface constructed a new word. This turn-taking-actuation interaction was repeated until the end of the activity.

4.2.2 Joint-actuation Condition. In the Joint-actuation condition the actuated-interface was active at the same time as the user, and completed the participant's words when relevant. After the participant began to construct a word by rotating the first few pillars, the actuated-interface was triggered to complete the word by turning the last pillar. The participant had 0.3 second after turning the one-before-last pillar to turn the last pillar, otherwise the actuated-interface completed the word (to a relevant word that was not used before, if one existed). The 0.3 second delay was determined based on a pilot study with six participants, verifying that this specific delay does not disrupt the activity flow.

4.3 Measures

A set of qualitative semi-structured interviews was used to evaluate the user's experience. Qualitative research methods allow for integrating participants' thoughts, attitudes, and emotional reactions into a useful and comprehensive representation of the data. It has the potential to capture the "how" and "why" underlying participant's experience. Specifically, a semi-structured interview enables flexibility during data collection while remaining grounded in a particular structure [4]. The set of interviews included a 'post experience interview' and a 'concluding interview'. The 'post experience interview' included questions concerning the experience with each interaction paradigm. The interview was conducted immediately after each condition and evaluated the participant's experience in the specific interaction (Turn-taking-activation or Joint-actuation) and included questions such as *"Please describe the experience"* and *"What do you think of the interaction with the actuated-interface?"*. The 'concluding interview' was conducted after the participant has experienced both interaction paradigms and focused on a comparison between them (e.g. *"Please describe the difference between the interactions"* and *"Which interaction did you prefer?"*).

4.4 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, 33 cm from the participant. Two cameras were located in the room for documentation and live stream video that was needed for the Woz controller.

4.5 Procedure

Participants arrived at the lab, signed an informed consent form, completed a demographic questionnaire, and were invited to enter the experimental room. Participants were informed that the room and actuated-interface were sanitized (due to COVID-19 regulations), that the experiment is video recorded, and that they can quit their participation at any time. 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 words as possible), the tangible interaction with the actuated-interface (assembling the words is performed by rotating the interface's white pillars) (see Figure 2), and the autonomous process of the actuated-interface, based on one of the two interaction paradigms: Turn-taking-actuation and Joint-actuation. Participants were told that the activity involves three phases with varying difficulty levels. In phase 1 they were asked to assemble words from two letters, by keeping the third and fourth pillars on the "blank letter". In Phase 2 they were asked to assemble words from three letters, by keeping the fourth pillar on the "blank letter". In Phase 3 they were asked to assemble words from four letters, by using all pillars. Participants were also told that the camera behind them is capable of sensing the letters they choose on the pillars and that it provides a designated sound indicating a successful assembly of a word. This feedback was attributed to the camera and not to the actuated-interface, in order to prevent additional autonomy attribution to the interface beyond the inherent autonomy of the actuated-interface. Each phase lasted 45 seconds and a designated sound indicated that the phase was over. Participants performed the activity in two conditions, Joint-actuation and Turn-taking-actuation. Each participant experienced the conditions one after the other (order counterbalanced) and received specific instructions concerning the interaction with the actuated-interface before the activity. In the Turn-taking-actuation condition participants were told that they will take turns in assembling words with the actuated-interface. After participants construct one word, the actuated-interface will construct a new word. This turn-taking will repeat continuously until the end of each stage. The participant was the first to construct a word in all stages. In the Joint-actuation condition participants were told that in some cases the actuated-interface will complete the words (but the participant will always be the one initiating the anagram). After each condition, the 'post-condition interview' was conducted in the experiment room, next to the actuated-interface. After the participants experienced both conditions, the 'post-activity interview' was conducted.

5 ANALYSIS

The semi-structured interviews were transcribed and analyzed using the thematic coding method [7, 13]. Thematic coding is a qualitative analysis methodology commonly used in HCI for identifying repeating themes in the data. Two independent coders analyzed the data, identifying repeating themes, comparing and contrasting their initial findings, until meaningful insights were generated. The analysis included 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 half of the data independently, verifying inter-rater reliability (Cohen's kappa=88%); (5) The two coders analyzed the rest of the data.

6 FINDINGS

383 quotes were analyzed (a quote was defined as a sentence including its continuation if participants further explained the exact same topic). The analysis led to four main themes: social interpretation of the interaction paradigms; user's perception of control; user's preferred interaction paradigm; and non-social interpretation of the interaction. We report on two additional themes that were less prominent yet are interesting, regarding the anagram activity itself and the tangibility aspects of the actuated-interface (i.e. tangible instead of digital interaction and interaction that involves two hands). In the quotes below, 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 participants' native language (Hebrew), which may explain the choice of "he".

6.1 Social Interpretation of the Interaction Paradigms

All of the participants (23/23) understood they interacted with a programmed machine, but at the same time perceived it as a social entity and provided a social interpretation to the experience. The interpretation was frequently defined by participants as *collaboration* with the actuated-interface or a *competition* with the actuated-interface. The frequency of the two different interpretations varied between conditions (see Table 2). In the Turn-taking-actuation condition, most of the participants (21/23) experienced the interaction with the actuated-interface as a competition, and only a few participants experienced it as collaboration. In the Joint-actuation condition, most participants (19/23) experienced the interaction as a collaborative activity with the actuated-interface, and only a few as a competition.

Table 2: Number of participants in each condition who interpreted the interaction as a different social experience: "competition" or "collaboration".

	Competition	Collaboration
Turn-taking-actuation	21	2
Joint-actuation	4	19

6.1.1 *Turn-taking-actuation.*

- "Competition" theme: Most of the participants (21/23) in this condition framed the interaction as a competition, where the actuated-interface's purpose was to construct more words than the participant and to construct them faster *"The actuated-interface built the word in two seconds, it took me longer, but I was motivated to beat him"* (p.1). Almost all of the participants in this theme (13/21) described it as a non-emotional experience and mentioned the limited number of possible words as the source of the competition *"Eventually there is a limited amount of words that you can create from the letters, you compete for these words"* (p.18). They also stated that the nature of the turn-taking-actuation interaction leads to a competitive context *"Because we built words in turns, it felt like a competition, like a game, I wanted to win"* (p.8). Some participants in this theme (5/21) described the competition as a *positive* interaction that challenged them *"I enjoyed it and had higher motivation, because I was competing against someone"* (p.16); *"I love competitions and that's what I felt here. If I wouldn't be able to build words I would feel like I've lost in the competition"* (p 7). These participants also mentioned the actuated-interface's ability to quickly find words as an important feature of the game, making it more engaging and interesting *"He was very quick in finding words and I had to play against him, it was nice and interesting"* (p.14).
- "Collaboration" theme: Only two participants in this condition (2/23) framed the interaction as a collaborative activity, where the actuated-interface's purpose was to assist them in finding as many words as possible *"Even though you work in turns it felt more like a collaboration for finding words"* (p.12). They described *positive* aspects of the interaction *"He didn't interfere with what I was doing, he was collaborating with me instead of competing with me"* (p.9). They expressed a feeling of a team working together by using the pronoun "we" *"I felt that we are succeeding, it was fun working with it"* (p.9).

6.1.2 *Joint-actuation.*

- "Collaboration" theme: Most of the participants (19/23) framed the interaction as a collaborative activity, in which the actuated-interface's purpose was to assist in word finding *"He completed me, I started a word and he completed it"* (p.24); *"He was like an assistant, his purpose was to help me"* (p.3). Most of the participants in this theme (14/19) described the collaborative interaction using *positive* terms. They stated that the actuated-interface helped them when they were stuck and couldn't think of words, *"When I had to create 4-letter words it really helped me, I didn't know what to do, nothing came to mind. It was nice when it helped"* (p.15) or when encountering difficulties *"I felt I was in a challenge with the actuated-interface and I realized that it can help me during the challenge"*(p.8); *"It supported me when I couldn't come up with a word"* (p.8). Some participants also stated that the actuated-interface completed the word they were already thinking about, and were pleased with this synchronization *"In some cases it completed a word that I had in mind, we were in a flow"*

Table 3: Number of participants which perceived the interaction in relation to aspects of control: "Fight for control", "Give-up control", and "Need for adaptive control". Some participants discussed more than one aspect of control. (+) and (-) under "Fight for control" represent either "I was in control" (+) vs. "I had to fight for control" (-).

	Fight for control	Give up control	Need for adaptive control
Turn-taking-actuation	2+	1	1
Joint-actuation	19-	10	12

(p.14). They further mentioned that the actuated-interface constructed words that they were not considering, and they enjoyed it *"He surprised me with new words, I enjoyed it"*(p.19). Participants also perceived the actuated-interface as an entity *"It felt as if it was much more alive, as if it was with me, a partner performing the task with me"*(p.15). A few participants in this theme (5/19) perceived the collaboration with the actuated-interface as a *negative* experience. They felt that the actuated-interface was intrusive *"He helped when I didn't need any help, it was annoying and frustrating"* (p.12) and interfered with their wish to enjoy the challenge that the game offers *"He helped and made the game much easier, it was annoying, I wanted to do it by myself"* (p.10). They were especially upset when they already came up with a word and started to assemble it *"I had a word in mind and it changed it to a different word, it was irritating"* (p.4).

- "Competition" theme: A few of the participants (4/23) framed the Joint-actuation interaction as a competition where the actuated-interface's purpose was to beat the participant in word completion *"It felt like a competition, I tried to create a word and it turned it to the other direction to create a different word"* (p.1). Two participants described the experience as a competition using *positive* terms *"It was amusing, he competed with me over the words, I am surprised of how I enjoyed it"* (p.16). Participants also stated that the feeling of competition increased the interface's animacy *"It was more authentic, I felt as if I was competing against another human"* (p.1).

6.2 Perception of Control

Almost all participants (22/23) discussed different aspects of control related to the interaction with the actuated-interface. Some participants discussed more than one aspect. This theme was discussed frequently in the Joint-actuation condition (22/23) and only rarely in the Turn-taking-actuation condition (4/23) (see Table 3).

6.2.1 Perception of Control within Turn-taking-actuation. When experiencing the Turn-taking-actuation interaction paradigm, participants only discussed positive aspects related to control. They specifically mentioned how they felt in control during the interaction *"I could build my words when it was my turn, he waited for his turn, he didn't interfere"* (p.18) and attributed it to the structure of the interaction paradigm *"Because the turns are clear, it provided me with a strong sense of control"* (p.2).

6.2.2 Perception of Control within Joint-actuation. From the 22 participants who discussed Perception of Control in the Joint-actuation interaction paradigm, 19 participants used terms that expressed a strong need to *fight for control* over the actuated-interface. At certain situations, participants (10/22) also expressed an opposite pattern of *giving up control* and letting the actuated-interface lead the interaction. When discussing these aspects of the interaction, many participants (12/22) offered ideas for changing the behavior of the actuated-interface. They suggested a more *adaptive control*, and wanted the actuated-interface to be sensitive and aware of their needs. Participants suggested that the actuated-interface will take control only when its assistance is relevant (i.e. when the participant can't think of a relevant word), and would not take control when help is not needed (i.e. when the participant has a relevant word in mind).

- Fight for control: Most of the participants (19/23) reported a need to fight for control over the interaction. In many cases they rejected the actuated-interface's actions and described it as intrusive and dominating *"He took over my ideas, it was not a competition, it just took over"* (p.12); *"He was rude, he wouldn't let me turn the letters"* (p.18). Participants described the interaction as a fight between them and the actuated-interface *"When I tried to build a word he interrupted me, so I interrupted him. He bothered me. I don't like being bothered"* (p.9). Some participants even tried to find ways to prevent the actuated-interface from completing words *"I tried to fool him, I built words in the opposite direction, from the last letter to the first letter, that way he didn't bother me"* (p.18). In some cases they spoke freely to the actuated-interface and used "first person" phrasing asking it to let go *"Do not tell me what to do, I know where I am heading"*(p.16). They were frustrated by the actuated-interface's involvement *"He didn't even give me a chance, he just cut me off"*(p.16) and felt helpless *"I experienced lack of control, as if someone else is deciding for you"*(p.18).
- Giving up control: In some situations during the interaction participants (10/23) decided to let the actuated-interface lead the game for them *"I just turned the first letters to see how it will complete it into words"* (p.16). They explained that they counted on the actuated-interface's abilities *"I understood that I can trust his judgement"*(p.14). They explicitly stated that they gave up playing the anagram game *"at this stage I stopped playing with the letters, instead I was playing with the actuated-interface"*(p.6). In some cases they stated that they just accepted the interface's "wish" to complete the words *"Ok, you want to complete the words, here are a few letters, let's see what you can do"* (p.4).
- Need for adaptive control: Several participants provided ideas on how to improve the interaction with actuated-interfaces, suggesting adaptive control *"It should help me only when I*

cannot find a word" (p.12). They explained that the actuated-interface's control can be very beneficial in specific cases but not in all. They wanted the interface to recognize these situations and adapt its behavior accordingly *"It should recognize when I encounter difficulty, and it should be sensitive, it should also release its control when I resist"* (p.18). They asked for a communication channel with the actuated-interface *"I want to speak with him or just signal when I do not want him to take over"* (p.12).

6.3 Preferred Interaction Paradigm

Participants' preferences of an interaction paradigm varied, with a slightly higher preference for the Turn-taking-actuation interaction paradigm:

6.3.1 Preference for Turn-taking. 12/23 participants preferred the Turn-taking-actuation paradigm. They attributed their preference to their personality *"I think that this actuated-interface reflected my personality. I like competitions, so I felt it was competitive"* (p.18). In some cases they stated that the interaction was more interesting since it was challenging *"He found its own words and I had to think harder, it was more challenging in a positive way"* (p.14). Some participants preferred the Turn-taking-actuation interaction since they found it to be more similar to a game *"He played with me or against me, it was fun"* (p.18). Other participants explained that they preferred this interaction paradigm because the actuated-interface was more polite *"He was waiting patiently for me to finish my turn. There's something very human and thoughtful about it"*(p.15).

6.3.2 Preference for Joint-actuation. 7/23 participants preferred Joint-actuation, framing the interaction as collaboration, and attributed their choice to their personality *"In general, I prefer to collaborate with others rather than compete"* (p.22). In some cases they also stated that they preferred it since they needed help *"When I tried to build 4-letter words I was glad I had the actuated-interface that could complete the words based on the first letters"* (p.11). Other participants preferred this interaction as they perceived the actuated-interface as another entity *"I liked it more because he felt very much alive, like it was responding to me"* (p.15).

6.3.3 Preference for a Combination of Both Conditions. 4/23 participants stated that they would prefer a combination of both conditions *"I don't have a preference, I would prefer something in the middle that combines both interactions"* (p.4). Some participants contributed their preference to their motivation *"For my confidence I would prefer the first interaction (Turn-taking-actuation) because I felt I succeeded there. But, if I would want to do something more unique and challenging, I would prefer the second interaction (Joint-actuation condition)"* (p.1). Other participants stated that they would prefer a certain interaction paradigm with certain adaptations *"If I'd had a more helpful partner, I would prefer the second interaction (Joint-actuation condition)"* (p.3).

6.4 Non-social Interpretation of the Interaction

In addition to the social interpretation of the interaction with the actuated-interface, many participants (18/23) also referred to the actuated-interface as a machine *"It's like a robot, a machine, it is programmed"*(p.4). The theme's frequency was slightly higher in the Turn-taking-actuation interaction paradigm (11/18), where participants commonly compared the interaction to playing with a computer *"It felt like a computer game, like playing against the computer"*(p.6). In the joint-actuation interaction paradigm (7/18), participants stated that they were explicitly considering the actuated-interface's mechanical features during the interaction *"There is no point in getting upset, it is a software"* (p.20).

Apart from the main four themes, 12/23 participants also discussed the word-completion abilities of the actuated-interface in the context of the anagram game. Some were impressed by the actuated-interface word-completion abilities *"It's pretty cool that it knows to build words on its own "* (p.7), while others were not *"I think it could be smarter. It could have built a more sophisticated word"* (p.19). Some participants felt inferior when they compared their performance to that of the actuated-interface *"I felt that no matter what I do, the actuated-interface would always have ideas. He's perfect"* (p.1), while others felt superior *"It was designed for me, that's its purpose. When it taught me new words it did its job"* (p.19). These different impressions about the actuated interface's word-completion abilities were not correlated with any of the two interaction paradigms: 4/7 participants in the Joint-actuation interaction paradigm and 3/5 participants in the Turn-taking-actuation interaction paradigm were impressed by its word-completion abilities, while 3/7 participants in Joint-actuation and 2/5 participants in Turn-taking-actuation were not impressed by its word-completion abilities.

Participants also mentioned the actuated-interface's tangibility. Participants appreciated the possibility for a two-hands interaction *"It was fun thinking of words while moving both of my hands"* (p.9), the unique hands-on tangible interaction *"The mechanism was unique, unlike the regular touch screen or keyboard"* (p.24), and the overall pleasant appearance and mechanics *"It's nice, appealing, and easy to manipulate"* (p.14).

7 DISCUSSION

In this work we present an actuated-interface that is not only a tangible interface but also an autonomous object that is perceived as an independent entity. The actuated-interface is a merge between an interface that the user is manipulating and an entity that is playing a word game with the user. We highlight two leading interaction paradigms of actuated-interfaces: Turn-taking-actuation and Joint-actuation, and evaluate both in a qualitative interaction study with the actuated-interface. Our findings reveal that all participants perceived the interaction as a social experience *"I felt as if I was competing against another human"*.

The consistent interpretation of the interaction as a social experience is inline with the body of work in HRI concerning social interaction with non-humanoid robots [2, 9, 16]. However, these non-humanoid robots do not involve direct tangible manipulation of the autonomous entity (i.e. the robot). Our findings indicate that the tangible manipulation of the interface, i.e. participants using their hands to manipulate the autonomous entity, did not compromise the perception of the interface as a social entity with its own intent.

Participants' reactions to the different interaction paradigms revealed meaningful differences in the type of social interpretation they attributed to each interaction. Turn-taking-actuation was interpreted as competition, and participants perceived the clear turn structure and limited resources (i.e. number of words) as an indication for playing against an opponent. The Joint-actuation was interpreted as a collaboration and participants perceived the interface's attempts to take part in their actions (i.e. complete their words) as an indication for having a helper trying to complete the task with them or for them. Another difference was the emotional response associated with the interaction. Turn-taking-actuation generated low-valence emotional responses, while Joint-actuation led to high-valence emotional responses. The emotional responses were either positive, perceiving the actuated-interface as *responsive, helpful, supportive, and a partner*, or negative, perceiving the actuated-interface as *intrusive, annoying, irritating, bothering, cutting off, and interrupting*.

Another finding relates to participants' perception of control. During the Joint-actuation interaction paradigm, participants showed two opposite patterns: Fight-for-control and Give-up-control. The opposite patterns were sometimes expressed by the same users during the same interaction. A possible explanation for this finding is the varying level of difficulty participants experienced during the game. When participants experienced difficulties assembling words, they were more comfortable releasing their control and letting the actuated-interface lead the activity (Give-up-control theme). When they could easily assemble words and felt they were succeeding in the game, they strived for more control and did not want the actuated-interface to interfere (Fight-for-control theme). Participants' responses reflect that they expect the system to understand them, to recognize when they need help and when help is not needed. Participants suggested that the actuated-interface should adjust itself to comply with their needs *"I wish I could somehow tell him, 'wait a second, now I'm trying to assemble a word', and then he could help me only when I'm stuck"* (p.12).

Based on our findings, we present insights for designers of TUIs and actuated-interfaces:

- **Choose the level of autonomy:** Actuated-interfaces can involve different levels of autonomy, that range from systems that provide feedback to user's actions (as a technical aid or optimization), to systems that are an autonomous entity taking an active role in the interaction, a role that is similar to the user's role (e.g. construct words in an anagram game). Users interpret the latter type of autonomy as a social entity, with its own intent, regardless of the interaction paradigm (Turn-taking-actuation vs. Joint-actuation).
- **Choose your interaction paradigm carefully:** Distinctive interaction paradigms are perceived differently, leading to different interpretations (e.g. competition vs. collaboration), and varying magnitudes of emotional valence responses (e.g. high-emotional valence vs. low-emotional valence)
- **In Joint-actuation pay attention to users' perception of control:** Joint-actuation challenges users' perception of control. In some cases users *Fight-for-control*, striving to lead the interaction and unwilling to share the control with the system. In these cases users may feel deprived of control, which can lead to anger and frustration with the system. In other cases users may *Give-up-control*, letting the system lead the interaction and abundant their part in the activity.
- **Explore adaptive autonomy:** Be aware of the user's need for control when designing adaptive autonomy. One approach can be to design the autonomous system to monitor participant's reaction time and task complexity, and "propose" to take control by initiating movement. If the user is not interested in releasing control, s/he will hold the actuated element to stop the system's autonomous movement and regain control. If the user is not interested in releasing control, s/he will not touch the actuated element, allowing the system to continue with the autonomous process and complete the action. One example for such implementation can be Joint-actuation in password generation: the user starts by selecting letters for a password, if the user finds the task to be challenging (reflected in a slow reaction time), the system starts to intervene. If the user accepts the system's suggestion to take control (as described above), the system will continue and extend the user's generated "word" into a strong password.

We hope our insights can serve designers of TUIs in the process of creating TUIs that also serve as social entities.

8 LIMITATIONS

Our study has several limitations. In qualitative interviews the interviewers could unknowingly influence an interviewee's responses [26]. To minimize the risk, we followed a detailed interview protocol and increased our interviewers' awareness to the possible effect of their verbal and nonverbal reactions during an interview. Another limitation is the reliance on the participants' honesty, as they may be affected by the "good subject effect" [24]. However, in this study, there were no right answers and participants were ensured that any answer is helpful. The study results show that the user's answers varied between participants, indicating that they did not try to please the interviewer. We also acknowledge the difference between Turn-taking-actuation that utilized the WoZ technique in addition to the autonomous process, and the Joint-actuation condition that was fully autonomous. A possible limitation could be a perception of greater autonomy in the WoZ-operated Turn-taking-actuation, as participants experienced both interaction paradigms (the study was a within-participants experimental design). We verified that in both conditions the participants described the interaction using similar terms and did not mention any differences apart from the type of actuation. In addition, there were no differences between the conditions in the level of autonomy attributed to the actuated-interface and social interpretation of the interaction. Another limitation concerns the specific context of the interaction. The word anagram context involves a simple playful activity with little consequences. It is possible that a more complex context of interaction would alter the balance between the competition and collaboration interpretations. Moreover the specific context of a game can bias the interpretation of the interaction towards a social experience and limit the generalisability of our findings. To minimize this limitation, we made sure not to present the system as a social entity, not to present the activity using the term "game", and not use any movements that were previously associated with social gestures [44].

9 CONCLUSION

To conclude, our findings show that it is possible to design an actuated-interface that users will perceive both as a tangible interface and as a social entity with intent. The actuated-interface was designed to take a role that is similar to the user's role in the context of the interaction, unlike prior actuated-interfaces, that are commonly designed to optimize user's actions. The different interaction paradigms determined the specific social interpretation users attributed to the interaction. Turn-taking-actuation was typically interpreted as a competitive experience, while Joint-actuation was interpreted as a collaborative experience. The interaction paradigms also determined intensity of emotions and perception of control (or lack of control), with Joint-actuation leading to more intense emotions and higher sensitivity to their level of control in the interaction. We hope our work will encourage HCI researchers and designers to explore TUIs with dual functions, serving both as a technical aid for optimizing performance and as a social entity.

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