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‘MoleBot’: An Organic User-Interface-Based Robot That Provides Users with Richer Kinetic Interactions

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We introduce a new type of organic user interface that displays a 3D robotic creature, ‘MoleBot’ to provide a ludic experience inspired by traditional board games. To ensure fluid motions of the molehills cast by the ‘MoleBot’, the table surface combines horizontal rigidity with the vertical flexibility of over 15,000 movable pins. Users are enabled to kinetically interact with this creature via a joystick or gestural commands. We conducted user study sessions with 12 participants and classified the observed spontaneous play activities into 4 distinct categories: (1) enjoying simple ludic experience, (2) competing in skills, (3) mimicking realworld sports and (4) playing with a companion. In addition, a focusgroup interview with six video scenarios was conducted to explore the idea of potential applications and it was suggested that the ‘MoleBot’ can be used in interactive board-gaming environments and kinetically informative tabletops.

RESEARCH HIGHLIGHTS

- A robotic creature called ‘MoleBot’ was built utilizing over 15 000 actuated physical pixels.
- Users can enjoy kinetic interactions with the ‘MoleBot’ via a joystick or gestural commands.
- Groups of two displayed engagement and creative activities more active than one-person or three-person groups.
- Users tended to regard the ‘MoleBot’ as a controllable entity rather than an autonomous creature.

Keywords: organic user interface; physical transformability; kinetic interaction; ludic experience; game

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1. INTRODUCTION

Since the advent of computers, people have tried to improve the quality of our lives by digitizing daily activities and transferring them into the virtual world of computing, where everything is highly controllable and editable. The invention of the mouse and the graphical user interface (GUI) have accelerated this movement enabling a wide range of human activities such as writing, drawing, mailing, gaming, shopping and human networking to be mediated by the rectangular flat screen of a computer. Yet, while this abstract screen has increasingly empowered human beings, it has also brought about the loss of rich real-world interactions of everyday life.

Since the early 1990s, researchers in the field of computer science and human–computer interaction (HCI) have been proposing new ideas to mitigate this phenomenon. Weiser (1991) outlined the concept of ubiquitous computing where computation embedded into everyday objects allows people to freely utilize computing technologies in order to enrich their daily lives. On the basis of this concept, pioneering HCI researchers have tried to blur the clear boundary between the real world and the world of virtual computing. Fitzmaurice *et al.* (1995) suggested a graspable user interface, Ishii and Ullmer (1997) tangible bits and Rekimoto (1997) pick-and-drop interactions to bridge the two worlds seamlessly Their researches aimed to restore the physical richness of real objects in HCI.

In the past decade HCI researchers went further by coupling atoms and bits more tightly and fundamentally, as they began to embed interactivity into everyday objects. The unlimited flexibility of digital information that used to be confined to a rectangular flat computer screen began to permeate into mundane objects. In this context, the concept of an organic user interface (OUI) was suggested to support HCI. As Vertegaal and Poupyrev (2008) stated in a special issue of the Communications of the ACM in 2008, OUI is a new type of user interface that includes non-planar displays that may actively or passively change shape via analog physical inputs. 'Gummi' (Schwesig *et al.*, 2004) and 'PaperPhone' (Lahey *et al.*, 2011) illustrated this new approach. Here, the researchers designed novel OUIs with flexible displays and sensors by incorporating natural human gestures and paper into a mobile device as thin as a plastic film. Users then intuitively control the flexible device by bending it in various ways. The physicality of the interface provides users with rich passive haptic feedback and natural affordances for manipulation. Indistinguishable from its main body, input and output are completely embedded in the mobile device. Currently, computing technologies have begun to be embedded in everyday object around us and interacting with computers increasingly emancipates itself from a GUI and a mouse. There is a need for alternative ways of interaction within ubiquitous computing. OUI represents a new approach to addressing this shortage.

As research interests in the field of HCI have shifted from screen-based GUIs to real-world interactions off the screen around the 1990s similar trends have been observed in the field of media art. Rozin's 'Wooden Mirror' (Freyer *et al.*, 2008) and Kodama's (2008) 'Protrude, Flow' are exemplary pieces, which were intended to integrate digital information with physical objects for surprising artistic expressions. Rozin built a mirror with 830 square pieces of wood while each wooden pixel is controlled by a servo motor. As people appear in front of the wooden mirror, it reflects them instantly. Kodama built a shape-shifting, 3D sculpture with ferrofluid and magnetism. These works are based on tight coupling of information (bits) and material (atoms) on a lower level and provide us with unusual interactive physicality unparalleled in our ordinary life.

On the basis of the idea of ubiquitous computing, in the future, it is expected that computer-supported human activities with desktops or laptops could be performed even with ordinary objects. Everyday objects in the future would involve computing power and OUIs with which users can interact. Traditional GUIs have been confined to a flat rectangular screen, but OUIs would be completely embedded in everyday objects and implemented on the basis of the tight coupling of bits and atoms exemplified in the 'Wooden Mirror' and 'Protrude, Flow'. In consequence, OUIs should be organic or malleable, rather than flat or fixed. They can transform depending on a user's needs and on interaction scenarios. In Holman and Vertegaal's (2008) words, function may equal form in OUIs.

Human beings have dreamed of compliant powerful tools like OUIs for a long time. In the Chinese classic novel, *Journey to the West* (Wu, 2006), *Ruyi Jingu Bang* (compliant rod) is a magical weapon possessed by the Monkey King *Sun Wukong*. It can shrink as small as a sewing needle enough to be hidden behind an ear when not in use, yet when in use, the size or color of the compliant rod can instantly be adjusted depending on the situation. Evolving new technologies for interaction design is about making such age-old dreams of mankind come true. As there are so many possibilities in the development and evolution of OUIs in the future, one of the characteristics that distinguish OUIs from traditional user interfaces is physical transformability.

Consequently, this paper discusses the physical transformability of object surfaces and investigates new ways of interaction with transformable surfaces. Shape-shifting interfaces based on actuated pixels have been developed as a 3D shape display to support design activities, decision making and so forth. We proposed a new type of OUI that displays a 3D robotic creature to provide a ludic experience inspired by traditional board games. The kinetic interactions with the robotic creature are expected to make the gaming and HCI experience even richer. Because many daily activities are now performed on computers, we have become more inactive and sedentary at home and in the office. This sedentary lifestyle is an inevitable consequence of the lack of physicality in general HCI. By introducing an OUI-based robot, it is hypothesized that kinetic interactions via the robot would induce the user to become more physically active and to have more interpersonal interaction when gaming. This paper reports how the idea of an actuated surface with an identity was developed and implemented and how users and designers accept the new OUI for gaming experience or design purpose.

2. OUIs BASED ON ACTUATED PIXELS

2.1. Shape-shifting OUI surfaces

One of the pioneering researches in the field of shape display was the Project 'Feelex' done by Iwata *et al.* (2001). 'Feelex' consists of an array of 36 DC motors, a flexible screen and a beam projector. Actuators move up and down and transform the flexible screen to render a 3D contour and the beam projector casts the corresponding graphical image. Iwata *et al.* (2001) turned immaterial, optical pixels into touchable ones which provided users with responsive haptic interactions. Each pin of 'Feelex' detects the input force of a user's hand and displays the corresponding haptic feedback according to the rigidity of the object.

'HypoSurface' (SIAL, 2011) is a modular structure that can be utilized to build a large-size interactive wall display. It involves 896 pneumatic actuators that move with a speed of up to 60 km/h and have a stroke length of 50 cm. Metal tiles mounted on the actuators make a tessellated surface interpolating sparse 3D graphical outputs. The deformable surface creates compelling 3D animations on the wall such as scrolling texts and ripples. This interactive wall relief is powerful and fast enough to push away people who lean against it, so that people can experience an engaging physicality.

Poupyrev *et al.* (2004) proposed 'Lumen' as a novel shape display for calm computing. 'Lumen' employs shape memory alloy (SMA) to actuate physical pixels and to enable the structural minimization of shape displays. Pixels are densely arranged and each pixel is a movable light guide whose height and color can be actuated individually to display a 3D shape. 'Lumen' also involves custom-made smart skin sensors to detect and respond to a user's touch input. Integration of SMA-based actuation and touch technology creates a smooth organic animation allowing 'Lumen' to be used as an interactive calm display for an ambient computing environment.

Unlike previous examples, 'Shade Pixel' (Kim and Lee, 2009) is a different type of deformable physical display. It consists of three tiers, a 2D array of 77 solenoids, a plexiglas sheet with 7 by 11 holes and a flexible spandex. The spandex has magnets that attach the fabric to the solenoid iron cores. An iron core pulls the fabric to make a concave surface which casts a shade. 'Shade Pixel' uses shade to visualize information in a manner similar to cuneiform or sunken relief. It can be used as an ambient, peripheral display for its non-luminescent nature and simple appearance.

Leithinger and Ishii (2010) suggested a scalable actuated shape display which is named 'Relief'. 'Relief' has 120 motorized pins with electric slide potentiometers. The pins are covered with a flexible Lycra surface. Electric slide potentiometers in the shape display are employed for sensing user inputs as well as actuating the Lycra surface. When some graphical images such as a terrain is projected on the fabric surface, the surface can render the 3D shape of the terrain and a user can add input to the surface by additionally pushing some pins. Blackshaw *et al.* (2011) advanced this idea with 'Recompose' , building upon the 'Relief' table. An array of 120 pins in the system can be controlled by mid-air gestures. A depth camera and a beam projector are mounted above the table, so that users can manipulate a computer aided design (CAD) model by means of some gestural commands such as selection, translation, rotation and scaling.

The above-mentioned research has presented exemplary prototypes of shape-shifting surfaces based on 2D actuated pixels. 'Feelex', 'Relief' and 'Recompose' utilize a pin screen mechanism for making a rigid surface malleable enough to render dynamic 3D shapes. The systems involve a beam projector and an integrated graphical overlay onto the shape displays. In consequence, people can interact with graphical information more physically than in traditional CAD systems and get more realistic haptic feedback. The remaining projects are more focused on the esthetic value of physicality in interaction design. The shape-shifting physical surfaces in 'HypoSurface', 'Shade Pixel' and 'Lumen' are quite uncommon in the real world and people are not familiar with such surfaces. For that reason, the movement of the surface created by actuation looks otherworldly providing a stronger visual impact than similar visual images on the screen do. Some interaction designers and media artists have developed shape-shifting physical displays to take advantage of this phenomenon.

2.2. Spatial shape-shifting OUIs

In the field of media art, artists have tried to map a bit to an atom in the space and have explored the possibility of spatial shape-shifting objects. 'The Source' by Greyworld is an exemplary work installed in the London Stock Exchange building in 2004 (Parkes *et al.*, 2008). It is made up of 729 ($9 * 9 * 9$) spherical balls suspended on cables. Balls controlled by Python scripts can move up and down independently along the cable and form dynamic shapes, characters and fluid-like motions. 'The Source' responds to the status of the stock market and elegantly displays information with the formation and movement of its spherical balls.

Another monumental spatial shape-shifting object is 'Kinetic Sculpture' (Sauter, 2011) located at the BMW museum. Kinetic sculpture involves 714 metal balls suspended in the space. Each ball is connected to a stepper motor by means of thin steel wires and can be individually positioned at a specific location in space. The sculpture displays a 7 min long animation that depicts the creative design process of automobiles.

These two examples of spatial shape-shifting physical displays look quite distinct from the deformable surfaces mentioned above but have much in common in terms of the working mechanism. To form 3D organic surfaces, every pin's or ball's movement in the shape display is unidirectional along the longitudinal axis of the pins or wires. It is exactly the same as a pin screen display. For that reason, the shape-shifting surfaces or sculptures based on actuated pixels have malleability with high directivity.

2.3. Vision and reality of shape-shifting OUIs

An arising question here is what happens when we expand the malleability of the previous projects by eliminating the directivity. Futuristic concepts of computing technology, such as *Claytronics* (Goldstein *et al.*, 2005) and the liquid metal robot *T-1000* (Wikipedia, 2011) in the movie *Terminator 2* might be first associations. The combination of nanoscale physical objects and computing modules brings forth nanoscale robots called Claytronic atoms (catoms). These catoms interact with each other to form a 3D shape-shifting object. According to the

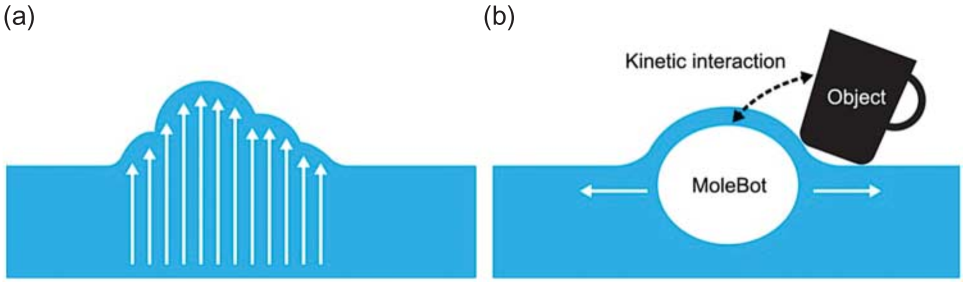

Figure 1. Transformable surface based on actuated pixels. (a) Shape display and (b) robotic creature based on actuated pixels.

future vision of *Claytronics* people would directly interact with physical CAD models made of catoms, instead of using a mouse and a GUI. Editing would resemble working with compliant clay. People would be able to enjoy the unlimited flexibility of digital information with even the most mundane physical objects around us.

As opposed to the promising vision of *Claytronics*, the current level of shape-shifting OUIs is yet quite rudimentary because of the restricted expressiveness and granularity of physical pixels. A lot of research on shape-shifting OUIs and technological breakthroughs is required to realize the dream of *Claytronics*. Nevertheless, we need to bridge the huge gap between dream and reality of shape-shifting OUIs and explore the possibilities by testing how they affect our daily life in terms of interaction design.

3. MOLE IN A TABLE

Much research in the field of HCI has been proposed by assuming their use in desktop environments. When Alan Kay conceived the idea of GUI at Xerox PARC in 1970, he designed it on the basis of familiar desktop metaphors. In the 1990s, HCI researchers applied video projections and vision-based tracking technologies to make a table interactive and efficiently support human activities with a computer. 'DigitalDesk' (Wellner, 1993), 'Urp' (Underkoffler and Ishii, 1999) and 'Augmented Surfaces' (Rekimoto and Saitoh, 1999) are well known projects that were intended to enable seamless interactions between the virtual world of computing and the real world in regard to table tops. Recently, HCI researchers have turned a tabletop into an interactive collaborative work surface by incorporating a big screen, multi-touch technology and tangible interfaces into a table to help users interact with GUIs on a tabletop more directly and intuitively.

'Lumen', 'TerrainTable' (Northrop Grumman, 2011) and 'Relief' were all designed as a table. These actuated surfaces on a table display 3D shape and some of them respond to user inputs. Shape-shifting OUIs based on actuated pixels would be used not only for rendering 3D shapes, but also for embodying a robotic creature on the surface. Further thinking has finally led us to the idea of an OUI-based robot on a table. We imagined a physical robotic creature living in a table and interacting with physical objects on the table surface. Whereas a conventional shape display sets the focus on rendering a dynamic 3D shape (Fig. 1a), the OUI-based robotic creature additionally divides the actuated surface into a fore and background. A robotic creature would be projected on the foreground while the background would be a stage for physical objects that can interact with the robot (Fig. 1b).

On the basis of this concept, a playful robotic creature 'MoleBot' was developed (Lee *et al.*, 2011). As the name implies, it lives underneath a tabletop and projects its presence with an organic deformation of the surface. The 'MoleBot' can move around in a table and create kinetic interactions with objects on the table. Although it is labeled as a robot, the 'MoleBot' distinguishes itself from other typical robots. The robot and the background stage are seamlessly connected, so that it is hard to distinguish one from the other especially when the robot stops. However, once it moves around, it would interact with surrounding objects just like a robot. When we compare the 'MoleBot' concept with previous shape-shifting OUI displays, the 'MoleBot' seems to be an independent agent kinetically interacting with users and objects rather than a passive shape display. It would provide users with a ludic gaming experience rather than adding up task-oriented utilitarian values.

4. IMPLEMENTATION

4.1. Rigid yet flexible surface with higher resolution and granularity of actuated pixels

The 'MoleBot' projects a molehill on a table surface that follows its movements. In order to make the molehill move with fluidity and interact with physical objects on the table, it was essential to make the rigid surface of the table flexible enough.

Previous shape-shifting OUIs such as 'Feelex', 'Lumen' and 'Relief' only have several dozens or hundreds of pixels. Consequently, it is not enough to render smooth organic surfaces and fluid movements. If, however, the resolution is increased up to tens of thousands of actuated pixels to get a reasonable quality, it would likely be an extremely daunting task in terms of budget and system complexity. 'HypoSurface' has 896 pins letting it display relatively detailed shapes, but the gap between juxtaposed pins is bigger than that of the other works, so that the module is quite bulky This seems inappropriate for implementing the 'MoleBot' concept on a table. Instead, a rigid yet flexible surface is needed to concurrently provide the necessary speed of actuation, higher resolution and a smaller pixel size for the desired level of physical interactivity with objects on the surface. Furthermore, the shape of the molehill remains the same. As a result, every pin of the 'MoleBot' should be actuated as a group of pins instead of a single pin.

On the basis of the analysis of the design problem, we found a solution in geology, as we reviewed the structure of a basalt columnar joint. It is formed by effusive rocks during the cooling of the lava flow. Most of the basalt columnar joints are a set of hexagonal columns with a honeycomb structure, so that every column is surrounded by further six columns. We found that a surface with hexagonal close-packed arrays of pins would resemble a thick sheet of flexible clay with enough malleability down the longitudinal axis of the pins. The huge bundle of pins can be deformed according to the shape of the underlying 3D rigid object.

4.2. The first prototype of 'MoleBot'

We built the first prototype of the 'MoleBot' table by transforming a 300 × 300 mm rigid table surface into a tessellation of more than 2700 small hexagonal pins that are 30 mm high. The pins are inscribed in a circle that is 6 mm in diameter and close-packed like columnar joints. The pins lean against each other, so that they can move up and down freely to create a molehill. We designed a 2D translating cam that has the same shape as a bell-curved molehill called 'mole cam'. The translating cam (also known as linear cam) is a mechanism that changes the direction and magnitude of reciprocating motion. As the translating cam moves backwards and forwards horizontally in a reciprocating movement, a cam follower moves up and down vertically according to the profile of the cam. The 'mole cam' has a strong neodymium magnet in it and is allocated just underneath the pins. As the 'mole cam' moves on the XY plane, the hexagonal pins create a linear motion along the direction of gravitational force like a cam follower. We have put a 5 mm plexiglas sheet underneath the pins and the 'mole cam' to support them. Finally, a puck with a strong neodymium magnet is allocated underneath the plexiglas sheet to control the 'mole cam'. The puck pairs up with another magnet in the 'mole cam'. As a result, the movement of the puck can be transmitted to the 'mole cam' and then to the pins, generating an organic physical deformation of the rigid table surface (Fig. 2).

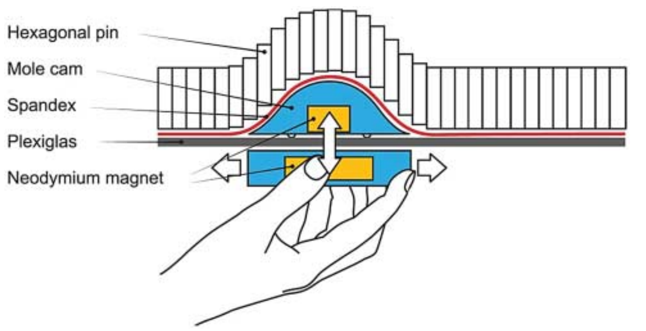

Figure 2. Sectional view of the first prototype of the 'MoleBot' table.

In the first prototype, it was impossible to actuate the 'mole cam' with the magnetic puck because of the strong friction between the 'mole cam' and the pins as well as between the 'mole cam' and the plexiglas sheet. To reduce the latter friction, we embedded three small ball transfers on the bottom of the 'mole cam', so that the friction was significantly diminished and the 'mole cam' could slide on the plexiglas sheet. Reducing the friction between the 'mole cam' and the pins was much more difficult, because of the number of pins on the table. To address this, we rounded all the pinheads to spherical faces and inserted a sheet of spandex between the 'mole cam' and the pins. The spandex layer created a smooth tangential surface that connected the 'mole cam' and the plexiglas sheet, so that it lifted some pins around the skirt of the 'mole cam' resulting in a remarkable reduction of friction.

As seen in Fig. 3a, we checked the feasibility of the 'MoleBot' concept as a new OUI by actuating the 'mole cam' by hand. The first prototype created a fluid movement of the 'MoleBot' as we had expected. We tested what kind of physical interactions

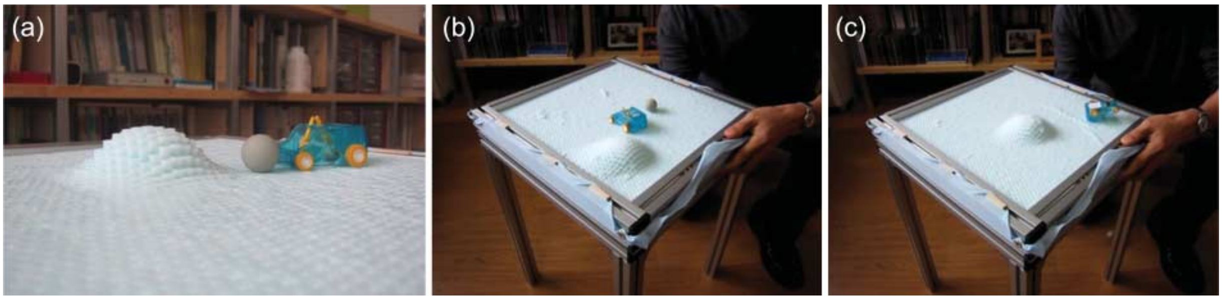

Figure 3. The first prototype of the 'MoleBot' table. (a) The bump of the 'MoleBot', (b) and (c) testing kinetic interactions with small objects.

between the 'MoleBot' and objects on the table were feasible The 'MoleBot' was able to carefully push objects and move them to other places (Fig. 3b). When we pushed objects with a higher speed, we were able to overthrow or even flip them (Fig. 3c). The table surface where the 'MoleBot' could move around was quite limited, so that objects easily fell off the table as we tested some physical interactions. We demonstrated the first 'MoleBot' prototype to faculty members and students from the industrial design department. Most of them reported that the fluid movement of the 'MoleBot' evoked an extraordinary sensual experience and gave them a strong visual impression, but the physical interactions remained relatively simple and restricted. As a result, we decided to make the first prototype large enough to be able to involve various physical interactions between the 'MoleBot' and the objects on the table. Furthermore, we explored the possibilities of enriching the physical interactions by taking into account further design factors such as interaction styles between the users and the 'MoleBot', a variety of terrain of the surface, the mechanical interactivity of objects and the electronic interactivity of objects.

4.3. The second prototype of 'MoleBot'

The second prototype of the 'MoleBot' table was then built on the basis of the same structure as the first prototype. The significant differences between the two prototypes were size and actuation method. The second prototype was as big as 1000 × 1000 mm. The size was almost the same as that of a coffee table in the living room. The actuatable area of the table was a 700 × 700 mm rigid flat surface which was composed of more than 15,000 small hexagonal pins. We put an 8 mm bakelite sheet underneath the pins to support more load instead of the 5 mm plexiglas used in the first prototype. As opposed to the first version, we utilized a XY stage with two bipolar stepper motors to actuate the 'mole cam' and render a dynamic molehill. The XY stage involved a moving head with a strong neodymium magnet and the moving head paired up with the mole cam on account of a strong magnetic attraction (Fig. 4). We set up the XY stage underneath the bakelite sheet. Two bipolar stepper motors of the 'MoleBot' table were connected to a PC via Phidgets bipolar stepper motor controller 1063 and controlled by a Processing program. This system configuration allowed us to make the behavior of the 'MoleBot' more interactive and programmable (Fig. 5).

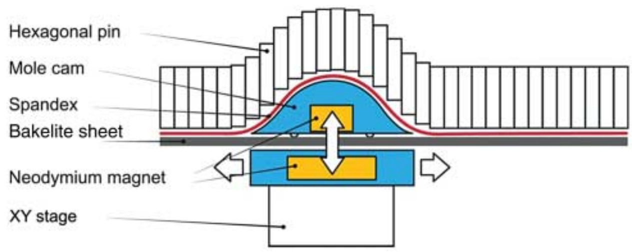

Figure 4. Sectional view of the second prototype of the 'MoleBot' table.

4.4. Interaction styles with 'MoleBot'

The 'MoleBot' projects its presence on the table with a one-inch high physical bump. It is a very simple robot that does not have any clearly articulated body parts such as a head, a torso, arms or legs, so the degree of freedom of its motion is quite limited in comparison with general robots. However, the organic deformation of the table surface by the 'MoleBot' creates a fluid motion and has some new possibilities of more sophisticated physical interactions thanks to the seamless integration of foreground robot and background table stage.

The combination of gravity, magnetic attraction and mechanical driving force helped to implement the physical interaction between 'MoleBot' and the objects on the table. As mentioned above, the 'mole cam' is basically driven by two stepper motors and a strong magnetic attraction. The combination of horizontal movement of the 'mole cam' and gravitational force creates the vertical linear motion of pins. A series of bell-curved vertical movements of pins generate a horizontal driving force for physical interaction. The 'mole cam' and the moving head of the XY stage are strongly magnetic. We designed some objects sensitive to magnetism such as balls with a magnet, small objects with magnetic switches or interactive

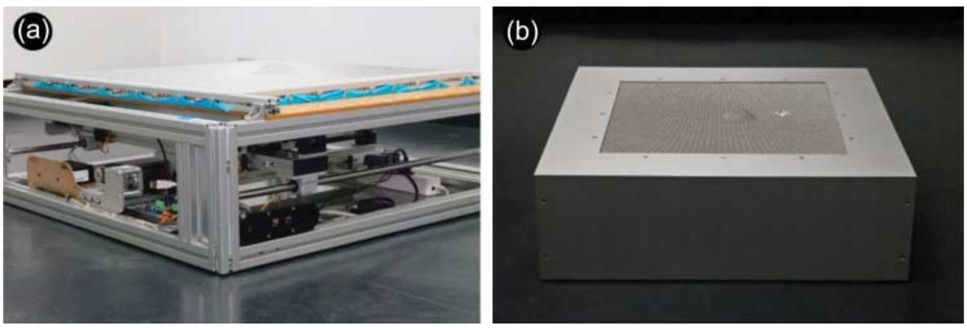

Figure 5. The second prototype of the 'MoleBot' table. (a) Inside structure of the 'MoleBot' table and (b) appearance of the 'MoleBot' table.

modules with a Hall effect sensor. The 'MoleBot' can either push objects with a horizontal driving force from the mole cam or pull something sensitive to magnetism with the neodymium magnets in the 'mole cam' and the moving head on the XY stage. Furthermore, the objects that are sensitive to magnetism detect the presence of the 'MoleBot' and respond to it when it approaches them (Fig. 6) (Lee *et al.*, 2011).

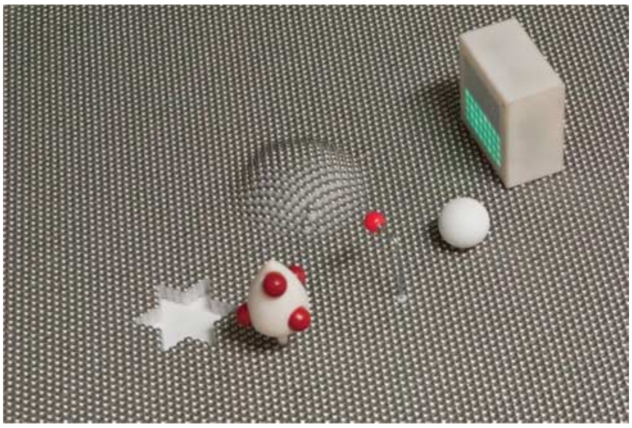

Figure 6. Small objects for kinetic interaction with the 'MoleBot'.

People can interact with the 'MoleBot' in two different ways. First, the 'MoleBot' can be controlled via a spring-loaded joystick. It is almost the same as remote control for a toy car or traditional arcade video games. We assigned the 2D input from a joystick to the position of the 'MoleBot' on the basis of a rate control algorithm. In this case, users can make the 'MoleBot' move around and then interact with objects on the table via the movement of the 'MoleBot' as illustrated in Fig. 7a. Secondly, we suggested an alternative way of controlling the 'MoleBot' on the basis of a spatial interaction. The movement of the 'MoleBot' is confined to the table surface, but the users' motion would go beyond these spatial restrictions. For instance, users might place some objects on the table or issue some gestures to express their intentions. We employed a *Kinect* as an input device to enable spatial interactions on the 'MoleBot' table. The *Kinect* is installed 1.5 meter above the 'MoleBot' table and it captures the users' body and objects on the table. The data from the *Kinect* involve vertical depth information as well as horizontal XY coordinates, so that the objects on the table can be identified simply on the basis of their heights. Furthermore, the 'MoleBot' system detects some mid-air gestures like a closed fist, an open hand or a hand motion with a specific wand.

We utilized a user's gesture or presence of some objects as an input to the 'MoleBot' system and built a basic interaction scenario as follows. There are some objects and gestures that

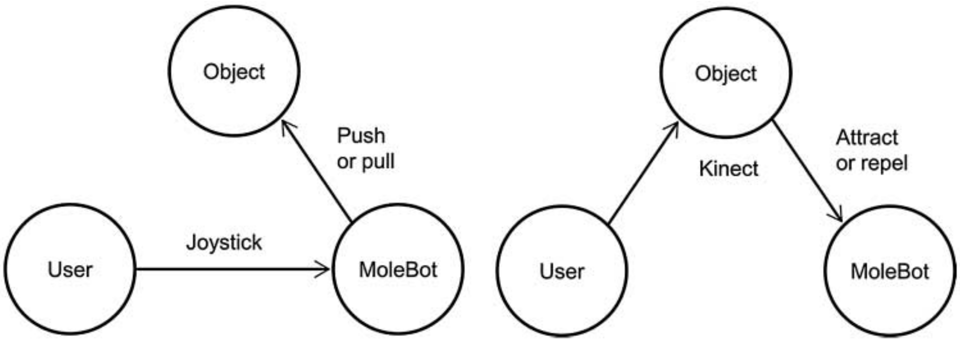

Figure 7. Interaction methods. (a) Joystick-based interaction and (b) Kinect-based interaction.

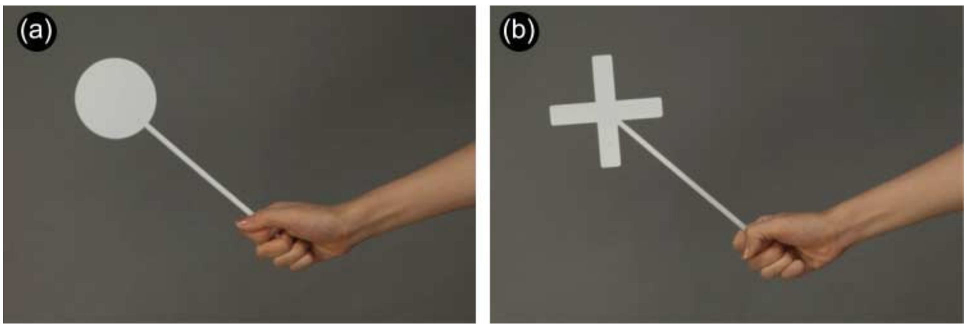

Figure 8. Wands for gestural interaction via Kinect. (a) A wand to attract the 'MoleBot' and (b) a wand to repel the 'MoleBot'.

the 'MoleBot' likes or dislikes. When the 'MoleBot' is getting closer to a preferred object, the object attracts the 'MoleBot'. On the other hand, a less-preferred object repels the 'MoleBot' (Fig. 7b). If a user presents a closed fist or a wand with a ball above the table and moves it around, the 'MoleBot' may follow the sign (Fig. 8). Even if the motion path of the 'MoleBot' has previously been programmed in various ways depending on application scenarios, the users can intervene in the autonomous behavior of the 'MoleBot' at any time by issuing gestural commands or laying out objects on the table to make creative interactions with the 'MoleBot'.

4.5. Reconfigurable physical game world

As discussed earlier, the 'MoleBot' was sufficiently implied to be a novel game platform rather than a general shape display. The pins that constitute the 'MoleBot' table surface were designed to be easily replaceable, so that users can reconfigure the terrain of the table surface according to their needs. For instance, users can make a small pit by replacing 30 mm high pins with shorter pins and build walls, mounds or buildings with longer pins. Hexagonal pixels can be replaced even with various small props such as trees or flowers, allowing people to build a miniature world on the table similar to that of a game board and control the 'MoleBot' to interact with those props. In addition, the 'MoleBot' can interact with any small objects of choice, giving people the creative freedom to design their own world of games with personal and mundane items (Lee *et al.*, 2011).

Figure 9. Generative toolkit.

Table 1. Groups of participants for the user study.

One-person groups	Two-person groups	Three-person groups
A (A1)	C (C1, C2)	E (E1, E2, E3)
B (B1)	D (D1, D2)	F (F1, F2, F3)

5. USER STUDY

The 'MoleBot' system was not designed as a solution for a specific HCI problem, but proposed as a potential design choice for the emerging research field of OUI. The system is relatively novel, so that it is hard to evaluate its value in comparison with other existing systems. As a consequence, we focused on an open-ended empirical study to understand how people accept the 'MoleBot' in their ludic activities. The empirical study consists of a user study that employed a generative toolkit and a focus-group interview (FGI) based on video scenarios.

5.1. User study with a generative toolkit

5.1.1. Methodology

The 'MoleBot' table is a new type of game platform that provides users with a deformable and reconfigurable physical surface for kinetic interaction. It is expected that users will be more creative and active in making their own games by laying out physical objects on the table. Consequently, to observe how people accept the 'MoleBot', we needed a toolkit to help users express their creative ideas on the table. Generative tools have been developed for a similar purpose in the fields of co-designing and user participatory design (Sanders, 2000 and 2008). To investigate many scenarios involving the 'MoleBot' in an open-ended manner, we adopted the concept of generative tools and applied this concept to a user study in a laboratory.

The generative toolkit for the user study, which is shown in Fig. 9 included the small objects shown in Fig. 6. Everything in the toolkit is sufficiently simple and ambiguous to lead participants to think of and express their ideas in a variety of manners (Sanders, 2000). In addition, for a richer kinetic interaction, the generative toolkit was designed to include objects of various sizes, proportions, degrees of roundedness and magnetic sensitivities; the objects were small or big, thin or fat, easy to roll or not and sensitive to magnetism or not. Prior to the start of the user study with a generative toolkit, the participants were given a simple modified instruction from Sanders' paper (Sanders, 2000) as follows. "*Use these components to express how you can play with the 'MoleBot'. You can do whatever you want, as long as it makes sense to you.*"

We recruited 12 young participants of 12.4 years in average. Ten were male and two were female. The participants were divided into two one-person groups, two two-person groups and two three-person groups. We conducted six user study sessions with the same condition as seen in table 1 because the size of the group might significantly affect how the members play with the 'MoleBot'.

The participants were allowed to control the 'MoleBot' with a joystick (Fig. 7a) or gestural commands based on *Kinect* (Fig. 7b). In the case of the joystick-based interaction, the participants simply navigated the 'MoleBot' on the table or were able to record some trace of the 'MoleBot' and play it back by using a button.

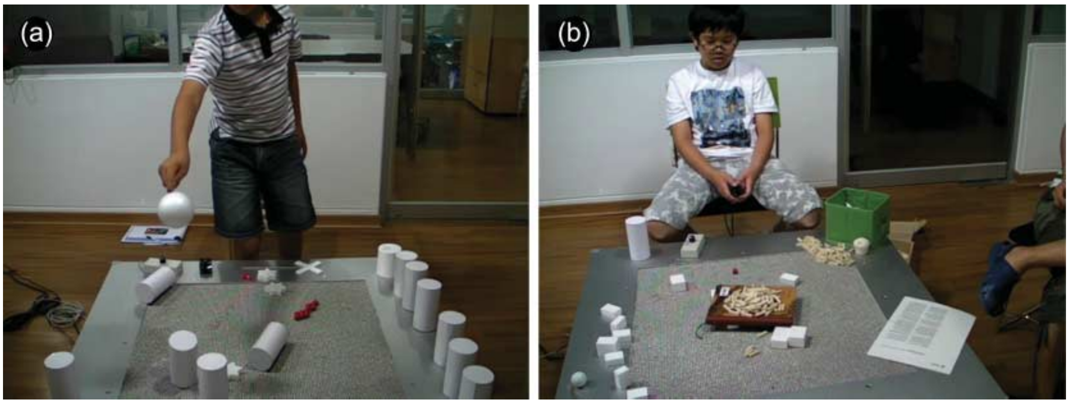

Figure 10. One-person groups in the user study session. (a) Group A and (b) group B.

When the participants interact with the 'MoleBot' via *Kinect*, the 'MoleBot' has more autonomy than in the joystick-based interaction mode. The 'MoleBot' has its own territory and path so that it moves around autonomously on the table. Only if a participant gives the 'MoleBot' some gestural command, the 'MoleBot' responds to the command and changes its path. For instance, the participant may get the 'MoleBot' away from its routine path by obstructing it with some object the 'MoleBot' dislikes. Holding a wand with a small ball above the table can also be an input to the 'MoleBot' system (Fig. 8a). This mid-air gesture may distract the 'MoleBot' from its own path and navigate it to wherever the participant wants. Prior to the user study session, a training session was given to every participant for 5 min and they acquired the skill without difficulty.

We conducted user study sessions twice at intervals of a week. The first time the participants looked at the 'MoleBot', they were required to evaluate the impression of the 'MoleBot' using rating scales that ranged from 1 to 7. The scales for the different characteristics included the following: unfriendly (1)–friendly (7), dull (1)–attractive (7) and unintelligent (1)–intelligent (7). The evaluation was aimed to measure the visual impression of the 'MoleBot' when it stops. Afterwards, the participants had a training session for 5 min and were given a generative toolkit as shown in Fig. 9. We gave 20 min to each group for a user study session. After the session, the participants were asked to repeat the evaluation on the impression of the 'MoleBot' and report their experiences on the basis of a semi-structured 10 min interview. We assumed that the second impression evaluation may capture the emotional changes after the participants experience the interactions with the robotic creature. After a week, the second user study session was conducted almost in the same way as in the first session except for the impression evaluation prior to the session. The participants were allowed to bring their own personal belongings and utilize them for playing with the 'MoleBot' if needed. After they finish their user study session, we asked them to rate the impression of the 'MoleBot' again (Fig. 10).

5.1.2. Results

During the training session prior to the first user study session, we could observe the reactions of the participants when they were first introduced to the 'MoleBot' and before any instructions were provided. During the user study sessions, we could observe a variety of play activities in which each group engaged.

Group A had only one member A1. In the training session, he knelt and bent over to observe the 'MoleBot' table surface carefully from the side. Next, A1 put his hand on the 'MoleBot' and patted it; then, he even tried to push it to move it in another direction. In the first user study session, A1 enjoyed navigating the 'MoleBot' with the wand for Kinect input and gathering small magnetic balls (Fig. 11a). In the second user study session, A1 stacked polystyrene bricks and built some structures on the table. Furthermore, he enjoyed knocking over those structures. A1 created a bridge and moved the 'MoleBot' through it without destroying it.

Group B also consisted of one member B1. In contrast to the other participants, he exhibited passive behavior and displayed little interest in the 'MoleBot' during the training session. In the first session, he built a maze with cylinders and made the 'MoleBot' go through the maze by using a wand without knocking down any objects. B1 also tried a joystick and enjoyed gathering scattered magnetic balls on the table. After the two activities, he suddenly lost his interest in the 'MoleBot'. In the second session, B1 brought books with him. He created a bridge by using his books and additional blocks and navigated the 'MoleBot' to take it down by knocking out one leg at a time (Fig. 11b). B1 also built dominos with his books or wooden blocks and knocked them over.

Group C had two boys. When C1 was introduced to the 'MoleBot' table, he knelt and observed the texture of the table surface. Then, C1 patted the 'MoleBot' and examined it by poking it with his fingers. After C2 observed C1's action, C2 became interested in the 'MoleBot' and tried to touch the table surface.

Figure 11. Two-person groups in the user study session. (a) Group C, (b) Group D.

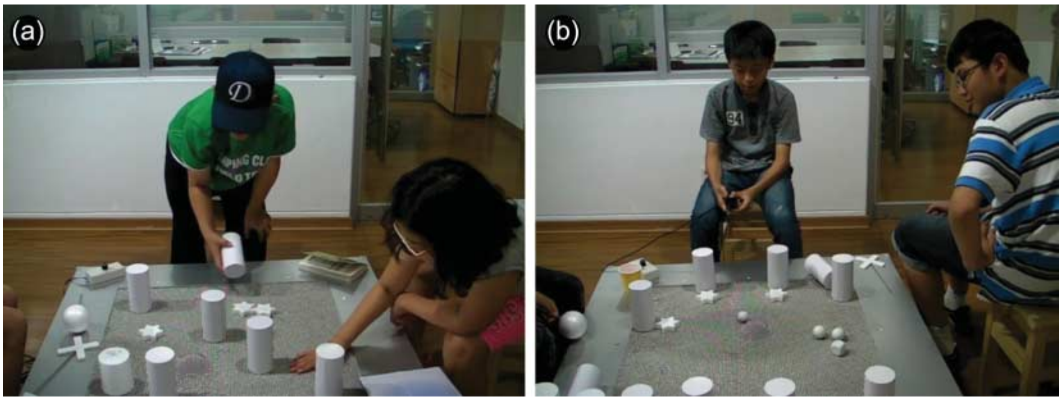

Figure 12. Three-person groups in the user study session. (a) Group E, (b) Group F.

In the first session of the user study, they put cylinders on the table and enjoyed a kind of avoid-the-walls game. Group C also created towns by appropriating cylinders and stars as buildings and controlled the 'MoleBot' to gather small magnetic balls and hide them around modeled trees. Group C tried a *Kinect* wand as well as a joystick in the first session. In the second session of the user study, the members of Group C treated the 'MoleBot' like a pet. They made a shelter for the 'MoleBot' and gave it a tune with their mobile phones to attract attention from it (Fig. 12a). Group C built a goal post for soccer using cylinders and made the 'MoleBot' go into the goal by using a joystick.

Compared with the other groups, group C frequently verbalized their ideas when they played with the 'MoleBot'. Below, we present a short dialog excerpt from the original transcript of the session because the verbal protocol accurately describes one of the typical manners of developing games using the 'MoleBot' and generative toolkit.

C1, C2: (They take turns putting several stars and cylinders on the table)
C2: "Do not put too many. You never know what will happen."
C1: "I want to control this." (Stops placing the cylinders and controls with the joystick) "I kill everything." (Knocks the cylinders over and finds that the star lights up by chance)
C1, C2: (Laughing together) (Start playing a game of knocking the cylinders over with the joystick)
C1: "I don't want to kill you."
C2: "It's cute, but don't you think it's too violent?"
C1: "Then, shall we do it this way?" (Separates several cylinders by adequate intervals)
C2: (Together, they help placing the cylinders)
C2: "Wait." (Puts a star between two cylinders)
C2: (Looks at the star) "You need to avoid it."
C2: "Avoid everything you can." "Can this operate the MoleBot?" (Points at the wand)
Moderator: "Yes, this can be done by switching the mode."
C2: (Goes over and brings the X-type wand)
C1: (Switches the mode and brings the O-type wand)
C1, C2: (They move the cylinders by collaborating. They play the game by having one person let out the 'MoleBot' and the other stop it)

While playing with an object selected from the toolkit, the two boys in group C suddenly found unexpected eye-catching interactions between the 'MoleBot' and an object such as when the star lit up when the 'MoleBot' approached. They combined the star with another interaction, knocking the cylinders over, which they enjoyed for a while. The two boys did not want to be too violent and tried to become more constructive in their play, so they invented a game that is a reverse of the general ludic activities. They inhibited themselves from the two interactions, which are lighting up a star and knocking over cylinders while performing a given task. When the participants in group C invented a new game, the process included some distinct sub-activities: finding some interesting interactions, defining the game pieces and rules of the game and adjusting the level of difficulty of the game. Interestingly, group C displayed a very cooperative manner in the user study session and we observed a very creative control technique in which they halted the 'MoleBot's' motion by using the 'O' and 'X' wands simultaneously.

Group D also consisted of two boys. They were more active and enthusiastic about the 'MoleBot' than any other group. As soon as group D was introduced to the 'MoleBot', D1 put his hands on the table surface and pushed it to investigate its makeup. D2 performed a similar action once he observed D1's behavior. Then D2 moved his hand onto the 'MoleBot', tried to push it and patted it. D1 also exhibited a similar level of interest in the 'MoleBot'. In the first session of the user study, we observed them enjoying simple ludic activities such as avoid-the-walls game and knocking over cylinders. Soon, they devised a bowling game with cylinders. In the game, the 'MoleBot' was regarded as a bowling ball. Each player moved the 'MoleBot' toward the cylindrical pins with a joystick and knocked over as many pins as possible at once (Fig. 12b). The verbal protocols and behaviors of the participants that we observed accurately describe the details of the interpersonal collaboration that occurred while the participants devised the bowling game with the 'MoleBot'.

D1: (Controls the mole with a Kinect)
D2: (Continues moving around the table, places the cylinder on the table in every movements made by the 'MoleBot') (The game of knocking over cylinders and using them to build structures proceeds)
D1: "Wait. How do I…?" (Stops the controls)
D1: "Place it again." (Builds a circular wall by moving the cylinders together)
D2: "You should put it in here (inside the circular wall) first." (He removes several cylinders. An arch wall is made)
D1: "Wait, let's do bowling." (Starts rearranging the cylinders while trying to put the 'MoleBot' inside of the wall using the joystick)
D2: "This goes here, and this goes there." (Arranges the cylinders into a wall)
D1: (Finds a similar form for bowling)
"This goes here, and this goes there." (Starts arranging the cylinders in triangular patterns)
D2: (Understands the intention of D1 while placing a cylinder in another place)
D2: "Then, four in here." (Points at the last line; together, the cylinders make a triangular pattern)
D2: "Leave it there." (Points at the remaining cylinder)
D1: (Moves the remaining cylinders to the borders of the table)
D2: "This seems fun."
D1, D2: (Starts bowling)

Like Group C, Group D also invented a new game by chance while they enjoyed kinetic interactions with the 'MoleBot'. Interestingly, their inspiration originated with the morphological similarity between the cylindrical objects' layout and the layout of bowling pins. This manner of inventing a new game was observed in other groups as well; for instance, Group C's mini soccer game used two cylinders from the generative toolkit. Group D also came up with modified avoid-the-walls game. First, a boy moved the 'MoleBot' on the corner of the table and surrounded it with cylinders. Then, the other boy had to escape the 'MoleBot' from there without falling down the cylinders. Group D built a simple curved maze and put a star at each end to mark a starting point and an end point. Then, they tried to navigate the 'MoleBot' along the maze without knocking over any cylinders. In the second session, Group D further developed the maze game from the first session and enjoyed those for most of the time.

Group E consisted of a boy and two girls. In the training session that occurred before the user study, a female participant E3 responded most actively to the 'MoleBot'. She spontaneously inspected the 'MoleBot' and patted the table surface. Another female participant E1 followed E3's actions. In contrast, a male participant E2 maintained a wait-and-see attitude while the girls played with the 'MoleBot' and exhibited less active behaviors than the girls afterward.

Group E enjoyed games together in the first session, but divided into a one-boy group and a two-girl group in the later session. In the first session, like other groups, they started knocking over cylinders with a joystick and a *Kinect* wand. Then, they attached magnetic balls on the modeled trees and tried to move the 'MoleBot' to harvest them with the wand. Interestingly, Group E tested the autonomous 'MoleBot' mode on the basis of the *Kinect* input and trapped the 'MoleBot' by surrounding it with cylinders (Fig. 13a). In the second session, the group split into two parts. Two girls spent most of the time building a city on the table and the other boy enjoyed insignificant ludic activities by himself. Two girls reported that the boy frequently destroyed something they built by driving the 'MoleBot', so that it was hard to play together.

Group F involved three boys. When they were introduced to the 'MoleBot', the boys bent over or knelt and inspected the table carefully without touching the surface. All the members were interested in soccer and they devised several games based on the sport. The following verbal interactions occurred a few minutes after the first session of the user study began.

> *F2: (Plays a game of avoiding the cylinders using the Kinect)*
> *F3: (Happens to place a star near a cylinder and discovers that the star's light turns on) "Change it to the joystick." (Controls with the joystick)*
> *F2: (Picks up two cylinders and gestures as if trying to place them somewhere)*
> *F3: (Navigates the 'MoleBot' between F2's cylinders)*
> *F2: (Happens to find the 'MoleBot' between the cylinders) (Hands over the joystick to F1 after navigating with it)*
> *F1: (Discovers that the star had moved because of the 'MoleBot')*
> *F2: (Discovers the similarity between the cylinders and goal posts.) "Want to play soccer? Place this wall like this." (Places two cylinders on top of the table like goal posts and places a ball on the table) "Navigate the ball like this…" (Uses the joystick to move the ball between the cylinders)*
> *F3: (Places the lighting star in front of the walls)*
> *F2: (Turns on the light of the star by steering the ball with the joystick)*
> *F3: "Put this (pointing at the star) in there (the ball into the goal), not turning it on"*
> *F2: "I need to time it"*
> *F3: "Can you score it?"*
> *F2: "Yep" (Cylinders fall while he steers the ball) "No…" (Sighs)*
> *F3: "It's because the robot is so round" (Touching the 'MoleBot') (Rights the fallen cylinder)*
> *F2: (After scoring a goal on the next try, changes into the Kinect mode)*
> *F1: (Holds the wand)*
> *F3: "Score it with that" (Pointing at the wand)*
> *F1: (Starts controlling the ball with the wand) (Subtle movements are not controllable and the ball keeps rolling sideways)*
> *F2: "Not that (ball), do it with this (box)" (Releases the box ball without corners)*
> *F1: (Plays soccer game with the box-shaped ball)*

Group F were inspired to invent 'MoleBot' soccer because of the similarity of the layout of the cylinders and that of goal posts that they observed while they were playing with the cylinders. This occurrence is quite similar to that found in Group D. The morphological similarity might tend to inspire users to mimic games or sports from the real world. The boys built a goal post with cylinders and put stars around the cylinders. The stars lit up when the 'MoleBot' was close to them. They navigated the 'MoleBot' carefully to drive a small ball toward the goal without lighting up the stars (Fig. 13b). Interestingly, the boys used the stars to increase the level of difficulty of the game and introduced a box-shaped ball to provide users with more control. A joystick and a Kinect wand were utilized for the game. It required higher dexterity, but they visibly enjoyed the game. In the second session, one boy brought a mole-shaped clip holder. When gathering small magnetic balls, he found that the clip holder attracted the balls and enjoyed magical kinetic interactions between the 'MoleBot', the small balls and the clip holder.

In the user study with a generative toolkit, we observed that the 'MoleBot' induced the participants to become more active and physical especially when the groups contained two or three people. When one participant navigated the 'MoleBot', the other participant spontaneously responded to the movement and he or she tried to actively touch it. A participant picked up an object and then put it in the path of the 'MoleBot' to create some kinetic interactions. Sometimes, a participant drove the 'MoleBot' to his colleague and gave him a chance to feel the speed of the movement by hand. In contrast, in the one-person groups, it was difficult for the participant to touch the 'MoleBot' while he controlled it.

The participants were not given any games, but rather were required to invent their own games during the user study. Consequently, we discovered that the participants naturally tended to take separate roles, depending on the situation and they exchanged their roles frequently. For instance, while one participant navigated the 'MoleBot', the other placed small objects on the table to design a game. One participant is a type of game player and the other is a type of game designer. The participants typically exchanged positions when they switched their roles and they even moved around the table frequently while playing with the 'MoleBot'. We observed this tendency most frequently in groups C and D. If we had provided the participants with a ready-made game and table setting, we could have observed quite different interpersonal interactions.

We summarized the major results of the user study in terms of activity, object and interaction method as shown in table 2. The interaction with the 'MoleBot' by using a *Kinect* wand was frequently observed in the first session, but hardly seen in the later sessions regardless of the group. As the participants were getting familiar with the 'MoleBot', they had a tendency to choose more direct ways to steer the 'MoleBot'. Most participants appreciated the naturalness and magic of gestural interactions with the Kinect wand, but seemed to have slightly more difficulty in controlling the 'MoleBot' especially when precise control was required. Furthermore gestural interactions required more physical movement. The members of Group C and E sometimes regarded the 'MoleBot' as an autonomous creature, so that they did not control the 'MoleBot' directly, but interacted with it by using gestural commands and some objects. In general, most participants preferred to control the 'MoleBot' with a joystick.

Table 2. Observed activities and objects used in the user study session (underlined objects are personal belongings brought by some participants)

Group		The first session	The second session
A	Used objects	*Cylinders, stars, magnetic balls*	*Wooden blocks, balls, polystyrene blocks*
	Activities	Spinning the 'MoleBot' round and round (Kinect) Gathering magnetic balls (Kinect)	Stacking and knocking over layers of objects (Joystick) Rolling a ball down the slope (Joystick) Creating a bridge and moving the 'MoleBot' through it without knocking it over (Joystick)
B	Used objects	*Cylinders, stars, magnetic balls*	*Wooden blocks, polystyrene blocks*, *books*
	Activities	Avoid-the-walls game (Kinect) Gathering magnetic balls (Joystick)	Knocking over dominos (Joystick) Knocking over books (Joystick) Using books and polystyrene block to create a bridge and controlling the 'MoleBot' to take it down by knocking out one leg at a time (Joystick) Gathering magnetic balls (Joystick)
C	Used objects	*Cylinders, stars, fruits, trees, plates*	*Cylinders, stars, magnetic balls, balls, muffins*, *puzzle ball*, *gundam*, *lid*, *mobile phone*, *reel*
	Activities	Avoid-the-walls game (Joystick, Kinect) Creating towns (Joystick, Kinect)	Putting the lid on the 'MoleBot' (Joystick) Playing music to the 'MoleBot' Rolling table top objects (Joystick) Mini-soccer (Kinect) Knocking over walls (Joystick)
D	Used Objects	*Cylinders, stars*	*Cylinders, stars, polystyrene blocks*, *car*
	Activities	Avoid-the-walls game (Joystick, Kinect) Knocking over walls (Joystick, Kinect) Bowling (Joystick) Going into a pit (Joystick)	Going into a pit (Joystick) Maze (Joystick)
E	Used objects	*Cylinders, stars*	*Cylinders, stars, wooden blocks, trees, balls, plates, polystyrene blocks*
	Activities	Lighting up stars (Kinect) Knocking over walls (Joystick) Gathering magnetic balls (Kinect) Robot trapping game (Kinect)	Creating a town (Joystick) Knocking over dominos (Joystick)
F	Used objects	*Cylinders, stars, magnetic balls, balls, trees*	*Cylinders, magnetic balls, trees, plate*, *mole-shaped clip holder*
	Activities	Avoid-the-walls game (Joystick, Kinect) Knocking over walls (Joystick, Kinect) Mini-soccer (Joystick, Kinect) Maze (Joystick, Kinect)	Combating a mole (Joystick) Knocking over dominos (Joystick) Gathering magnetic balls (Joystick) Mole elimination game (Joystick) Robot trapping game (Joystick) Bridge-crossing game (Joystick)

The participants tried many activities in the user study sessions. We classified them and could find several distinct categories: (1) enjoying simple ludic experience, (2) competing in skills, (3) mimicking real-world sports and (4) playing with a companion.

The first category of activities—enjoying simple ludic experience—was frequently observed in the one-person groups and the early phase of the first user study session in the other groups. This category involved activities without rules or collaborations between people, such as gathering magnet balls and knocking over dominos or *Jenga*™ tower. The participants turned the simple ludic experience into the second category of activities, competing in skills, by employing a few game rules during the user study sessions. Going through a maze without destroying it is a good example. On the basis of the rule, participants could compete with other members in skills of manipulation like video games. The participants devised many simple games utilizing kinetic interactions between the 'MoleBot' and objects.

In Group D and F, the members tried to mimic soccer and bowling and designed similar games with the 'MoleBot'. The physical bump of the 'MoleBot' looked similar to a ball, so that some participants might have come up with such ideas. These activities belong to the third category—mimicking real world sports. Girls and boys in Group C and E treated the 'MoleBot' as a pet. Trapping the 'MoleBot', making a shelter for the 'MoleBot' and giving a tune to the 'MoleBot' with mobile phones belong to the forth category of activities, playing with a companion.

During the user study session, we measured emotional responses of the participants three times by means of 7-point rating scales, prior to the first session, after the first session and after the second session. This sample size is not amenable to statistical analysis, so that we summarized the descriptive statistics of the results.

In the case of the rating scale "*unfriendly–friendly*", there is a distinct difference between one-person groups and other groups. The members of the one-person groups feel less friendliness toward the 'MoleBot' than other participants. In addition, the progress of the user study session seems to have led the participants to feel friendlier about the 'MoleBot'. Even the members of the one-person groups were getting friendlier toward the 'MoleBot' after they observed the 'MoleBot' moving around on the table. From the observation, B1 suddenly lost his interest in the 'MoleBot' shortly after the start of the first user study session, but in the later session he brought his personal belongings and managed to play with the 'MoleBot'. Through the interview after the second session, we found that the boy had a negative preconception of robots. That is why the friendliness toward the 'MoleBot' in the one-person groups was negative until the first user study session. Nevertheless, it was interesting that the two-person and the three-person groups generally showed more positive response in terms of the "*unfriendly–friendly*" rating scale than the one-person groups (Fig. 14).

The second rating scale *"dull–attractive"* measured the extent to which the participants felt attracted toward the 'MoleBot'. The result indicates that most participants felt a positive emotion in attractiveness regardless of the progress of the user study session except that the one-person groups thought that the 'MoleBot' seemed dull after the first user study session. The one-person groups responded positively just before the first session and the response suddenly turned negative. As mentioned above, this incoherent result might have been caused mainly by the boy in Group B who lost his interest in the 'MoleBot' in the first session. Interestingly, the level of attractiveness does not seem to have been affected significantly by the kinetic interaction of the 'MoleBot' (Fig. 15).

In terms of the *"unintelligent–intelligent"* scale, the two-person and the three-person groups revealed the most positive responses toward the 'MoleBot' just after the first user study session. They felt that the 'MoleBot' looked less intelligent after the second session than a week ago. In the first session, the participants in the two-person and the three-person groups frequently tried to interact with the 'MoleBot' via gesture-based commands rather than with a joystick. They regarded the 'MoleBot' as a more autonomous entity at that time. When the participants in the user study session looked at the

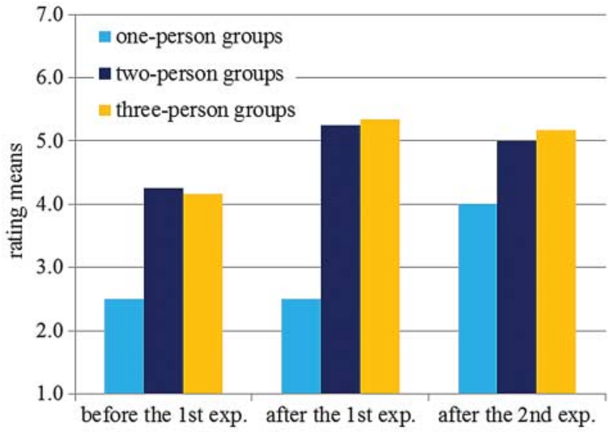

Figure 13. Emotional responses measured using an "unfriendly (1)-friendly (7)" rating scale.

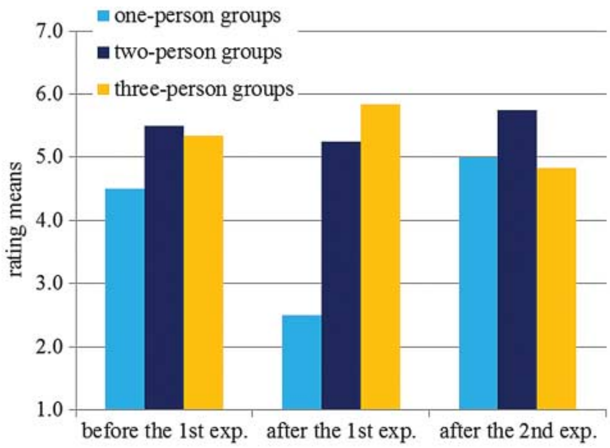

Figure 14. Emotional responses measured using a "dull (1)–attractive (7)" rating scale.

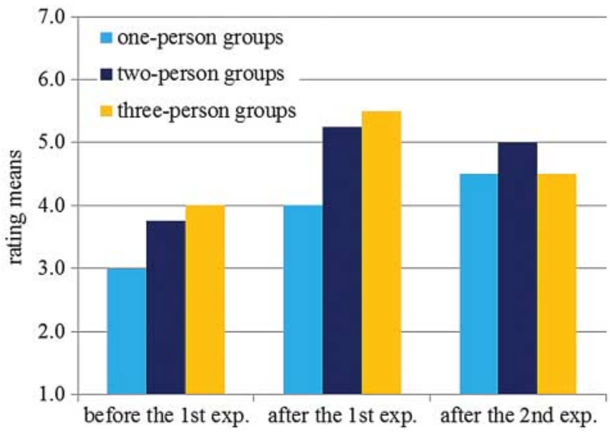

Figure 15. Emotional responses measured using an "unintelligent (1)–intelligent (7)" rating scale.

'MoleBot' for the first time, the 'MoleBot' stood still and they considered it to be unintelligent. But after they experienced some interactions with the 'MoleBot', their feeling had changed considerably (Fig. 16).

5.2. FGI with video scenarios

5.2.1. *Methodology*

The user study session employed simple and ambiguous objects to elicit a variety of ludic activities the participants can imagine. In fact, the ludic activities were subject to the interactivity of the objects on the table. To investigate more possibilities of kinetic interactions with the transformable organic surface, we designed interactive objects that can respond to the 'MoleBot' and developed ludic or game experience scenarios with the objects. The scenarios were implemented and videotaped.

We developed six different types of interactive objects: apple tree, tofu, RollBot, fragile castle, hexagonal maze and L-rod. The apple tree is a modeled tree including red apples which are sensitive to the strong magnetism of the 'MoleBot'. The 'MoleBot' can shake the tree and pick up the fruits that drop (Fig. 16a).The tofu is a simple rectangular volume that includes an 8×8 LED matrix, a piezoelectric speaker, tilt sensors and Hall effect sensors. As a result, it detects the presence of and kinetic inputs from the 'MoleBot' and responds to the input via video and audio (Fig. 16b).The RollBot is a two-wheeled robot small enough to move around on the 'MoleBot' table. Two players, one controlling the 'MoleBot' and the other controlling the RollBot, fight over a ball and the person who puts the ball into a goal wins the game (Fig. 16c). The fragile castle is built with small wooden blocks like those of *Jenga*™. Players can create a small game world with the castles. They are given some tasks that should be carried out without destroying the castles (Fig. 16d). A player builds a hexagonal maze by replacing some pins with longer ones. The player who can control the 'MoleBot' to fetch a ball and place it on a specific destination in the maze wins the game (Fig. 16e). The L-rod is an L-shaped rod with a strong neodymium magnet, so that it automatically orients itself in the direction of the 'MoleBot' (Fig. 16f).

We recruited four female university students (24.1 years in average) majoring in industrial design and having much more experience in interaction design than the participants in the user study session. The video scenarios were shown to the students. The interviewer of the FGI requested them to talk to each other about the video scenarios and to come up with more creative interaction scenarios. The participants were given 2 h for FGI and allowed to express their ideas even with idea sketches if needed.

5.2.2. *Results*

The group of four participants discussed the given six video scenarios and explored more possibilities in kinetic interactions with the 'MoleBot'. It seemed that the transformable table surface gave the participants an unusual sensual impact that has rarely been experienced in the real world. The ideas from the FGI for 2 h were classified into four categories as follows.

'MoleBot' as an artistic medium. When the 'MoleBot' moves around on the table, it deforms the table surface kinetically and carries a strong magnetism with it. As a consequence, the 'MoleBot' would create some physical changes in the objects on the table via physical power. For instance, if we deploy some material on the table, which easily changes its color according to the kinetic input from the 'MoleBot' or the rapid change of magnetism, people draw something on the table and express their ideas in an artistic way (Fig. 17a). The 'MoleBot' can pull something by means of its magnetism. Suppose there are threads with a small steel ball on the table and some longer pins sticking out from the table surface, the 'MoleBot' can draw patterns by moving around a thread on the table (Fig. 17f). The frequent movement of the 'MoleBot' can induce electricity in the objects on the table and the electricity may actuate some kinetic sculptures, such as spinning an array of pinwheels (Fig. 17h).

Mixed reality game with visual augmentation. The 'MoleBot' system does not include any video projection, but one of the FGI participants suggested that visual augmentation with a beam projector would enhance the game experience with the 'MoleBot'. For instance, some artificial creatures can be projected on the table and the 'MoleBot' traces the creature to win a point. If users set up the game environment by putting some real objects on the table, the 'MoleBot' and the projected artificial creatures might be able to recognize the physical world and would behave and interact with each other (Fig. 17c).

'MoleBot' and interactive tangibles. Tangible interaction can effectively evoke children's interest and curiosity in serious education or game activities. What if combing the 'MoleBot' and interactive tangible objects? Suppose there are blocks with alphabet on the table, a child would pick up some of them by navigating the 'MoleBot' and group them to make a word. When the word is completed, the blocks sound that word (Fig. 17d). Buses and cars are closely packed inside walls on the table and only small space is left for the 'MoleBot'. It is a situation similar to a Rush Hour game. The 'MoleBot' should escape a red car out of the walls by pushing buses and cars (Fig. 17e). There is a laser and reflectors on the table. The 'MoleBot' can move the reflector and adjust the angles. Users make the light from the laser reach a target (Fig. 17i).

Interaction with other robots. Suppose there is a bird robot above the table and the 'MoleBot' is playing with a ball. The bird regards the ball as prey and flies down to snatch it. The 'MoleBot' should protect the ball from the bird. The bird robot has a strong magnet, so that it can take the ball just by sweeping

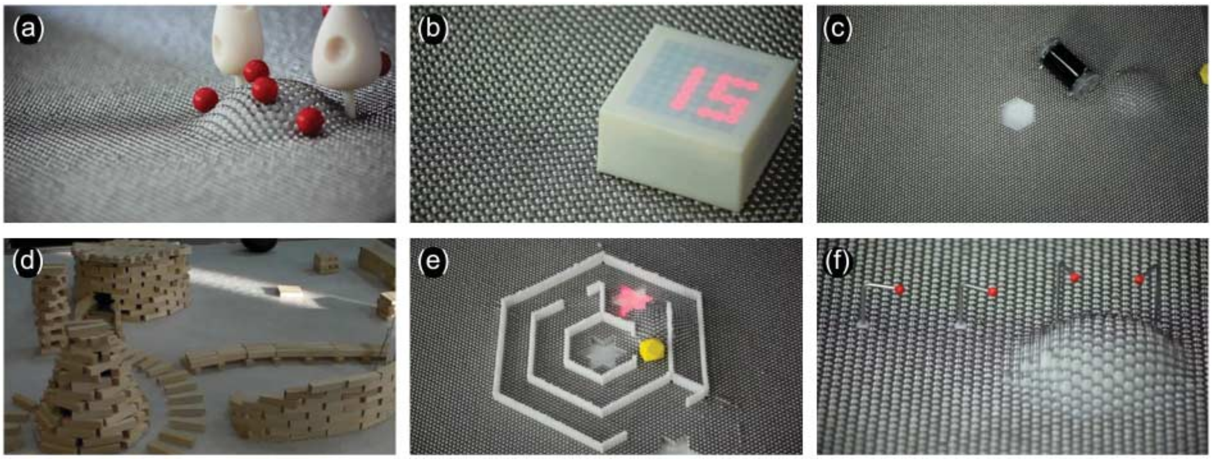

Figure 16. Video scenarios for FGI. (a) Apple tree, (b) tofu, (c) RollBot, (d) fragile castle, (e) hexagonal maze and (f) L-rod.

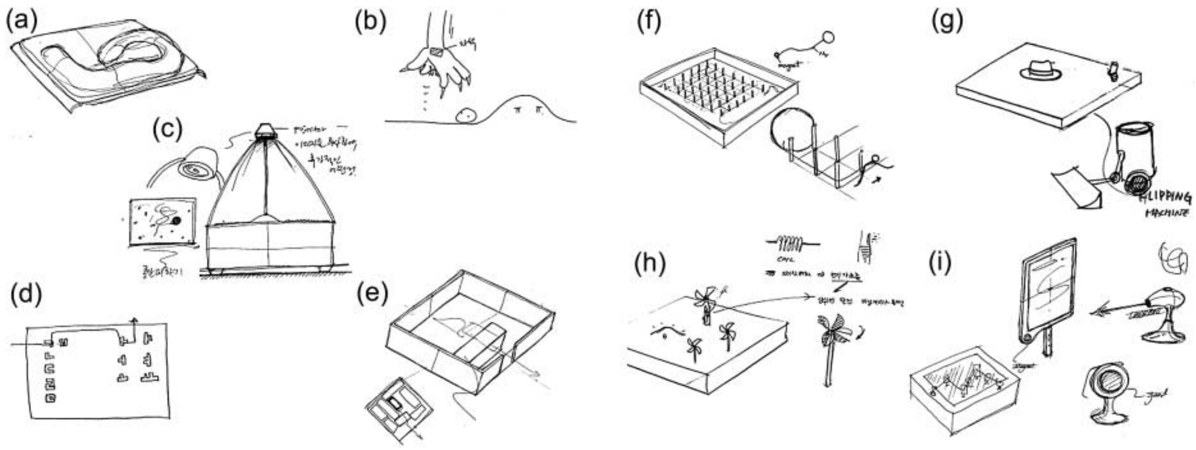

Figure 17. Sketches from the FGI with video scenarios.

over the table surface (Fig. 17b). Suppose the 'MoleBot' is wearing a hat and moving around on the table. Another robot is tracing the 'MoleBot' and trying to flip over the hat. If the hat is flipped, the 'MoleBot' loses the game (Fig. 17g)

6. DISCUSSION

6.1. Experience from kinetic interactions with the 'MoleBot'

Most participants in the user study session and FGI reported that the 'MoleBot' gave them a unique sensual experience, so that it stimulated their interest and evoked curiosity. From the results of the observation during the user study session, 9 out of 12 participants were quite engaged in the play with the 'MoleBot'. They enjoyed several different types of ludic activities or devised their own games through the kinetic interaction between the 'MoleBot' and the objects on the table. Their activities were created spontaneously and naturally evolved into other activities with the progressing user study session. Their personal belongings as well as mundane everyday objects could also be a toy when playing with the 'MoleBot'. Especially, the two-person groups displayed a great collaboration for setting up game an environment and enjoying it. This phenomenon is quite distinct from typical video games. In fact, it seems more similar to playing with ordinary toys rather than video games. Both girls and boys had a tendency to express their game ideas spontaneously just by laying out some objects on the table and enjoying various ludic experiences from the kinetic interactions. Supposing they had been given a radio-controlled (RC) car and the same physical objects in the user study session, how would they have played with them? As you might have seen a robot soccer competition, the play with the RC car would have involved far less variety in kinetic interactions

The 'MoleBot' table is one of various applications of a transformable physical surface based on actuated pixels. Each pin is equivalent to a pixel on the screen, but it is kinetically interactive. It has a higher resolution and granularity of physical pixels than any other previous works, so that it creates smooth physical transformations and organic kinetic interactions due to the seamlessness between the 'MoleBot' and the background table surface. Even though the 'MoleBot' table is not a fully actuated surface, the fluid robotic entity based on the predefined 3D shape makes the participants feel like they are interacting with a real animal beneath the table surface.

6.2. How to accept the 'MoleBot'

The participants in the user study session were given four different types of control methods: a joystick, a joystick with record/playback button, wands for *Kinect* input and objects for *Kinect* input. We expected that the participants would utilize the control methods in various ways. But the results were quite different from our expectations. In the first user study session, most participants just kept using a joystick after they tried out two or three methods out of all the given ones. Gestural input via *Kinect* seemed more intuitive and interesting to the participants but it was not utilized frequently.

Basically, the girls and the boys in the user study tended to regard the 'MoleBot' as a controllable game character rather than as an autonomous creature. We could observe similar tendencies in the FGI as well. The ideas from the FGI were largely about how to utilize the 'MoleBot' as a tool, a toy or new medium rather than how to interact with an independent entity. This result is thought to be caused by several reasons. First, the participants in the studies are too familiar with video games and RC cars, both controlled by a joystick, that they might have started to consider the 'MoleBot' as a controllable object. The gestural interaction with the autonomous 'MoleBot' was relatively unfamiliar to the participants, as the interaction methods lacked affordance for input and visual feedback, so that participants seemed to have some problems in figuring out what the 'MoleBot' is doing. Secondly, the gestural input required more physical demands because of the large size of the table. The participants had to hold a wand for a while to navigate the 'MoleBot' or keep laying out some objects on the table to induce the 'MoleBot' to perform a task. Thirdly, the programming level of the 'MoleBot' was not sufficient for the participants to accept it as a companion or pet. The reactions to the user input were designed too simple that it might have been difficult to persuade the participants to regard the 'MoleBot' as an artificial creature. If we improve the 'MoleBot' regarding the above-mentioned problems and if users are given only a gestural input method for interaction via *Kinect* we might get results quite different from the observation.

It was very interesting that there has been a big difference in the users' behaviors depending on the size of the user group. We found a big contrast between the one-person groups and the two-person groups. The inactiveness and monotony seen in the one-person groups makes sense. The opposite reactions from the two-person groups also seem reasonable in the context of the 'MoleBot' table. But when we are watching children playing video games, the situation would not necessarily be the same as in the 'MoleBot'. It would not be hard to find a boy who is engaging in the game in front of the screen all by himself. Why were the two-person groups able to enjoy the interactions with the 'MoleBot' more pleasurably than the one-person groups? As opposed to video games, in the user study session, the participants were not given game contents. They were required to build up the physical world of the game by themselves because that was one of the key design concepts of the 'MoleBot' table. The two-person groups could talk to each other and play a complementary role in designing a game and performing it. On the other hand, the participant in the one-person groups should do this activity by himself and thus, showed less interest in the user study session enjoying other insignificant ludic activities instead. Interestingly, in the three-person groups, the members split into two groups and displayed two different types of behaviors at the same time.

6.3. Potential applications of the 'MoleBot'

The user study and FGI gave us some ideas on the potential applications of the 'MoleBot'. The 'MoleBot' can be an *interactive gaming table* that would be simpler than video games but provide more substantial experience based on kinetic interactions. Users surround the 'MoleBot' table and talk to each other, so that it facilitates social interaction between people. To play on the 'MoleBot' table, users need to frequently move their body instead of just staring at a screen in a sedentary posture. For instance, interacting with the 'MoleBot' via real objects would be a good exergame to improve hand–eye coordination for children or elderly people.

What if making use of the 'MoleBot' in computer-mediated communication or HCI? The 'MoleBot' table can be a *kinetically informative tabletop*. For instance, when you get an urgent e-mail from your friend while talking on the phone, the 'MoleBot' may give you a nudge to take notice of it. Suppose people talk to each other on the table. The 'MoleBot' can serve people as a messenger by transmitting some objects for interpersonal communication. The 'MoleBot' can manage tangible tokens which represent digital information on the table, so that people would organize their tasks without even bothering to interact with a computer.

6.4. Limitations of the 'MoleBot' and user studies

On the basis of the vision of ubiquitous computing, the 'MoleBot' was designed as a physically transformable surface which can display digital information. It was implemented with over 15 000 tiny physical pixels, so that it satisfied with organic kinetic movements on the table surface. But the kinetic interactions were limited because of the localized actuation and the fixed shape of the 'MoleBot'. During the user study and FGI, some participants reported that if there are more than two moles interacting with each other, it would be much more interesting. Unfortunately, when we were dealing with tens of thousands of physical pixels, it was a fundamental problem that required an extremely daunting effort and technical breakthroughs.

We had another difficulty in conducting a user study. In order to observe how people accept the 'MoleBot', it should have been set up in a real-world context for a long term observation. It was too difficult to build a working prototype of quality that could be installed in the living room. As a result, we planned a user study taking place at a laboratory environment and focused on exploring a variety of ways that people interact with the 'MoleBot'.

Because we observed unexpected social dynamics in group E, the user study with a generative toolkit appeared to have been affected by the participants' characteristics and interpersonal relationships. Even if two groups were identical in terms of the number of group members and gender ratio, it would be unlikely to observe similar group activities because of uncontrollable variables regarding the participants. Furthermore, the generative toolkit was used to help participants express their game ideas in various creative manners, so it was quite difficult to draw some general conclusions from the observations of only six groups of participants.

We originally designed the empirical study in the hope that more players with 'MoleBot' could generate creative games, challenging their conventional playing habits. Indeed, the ludic dynamics observed in the study can be interpretable by the concept of social flow (Ryu and Parsons, 2012), so that we hypothesized that this collaborative flow experience would prompt more extra tasks to play by fostering greater motivation than one-person groups. However, this was not the case for the three-person groups, perhaps they were hampered by the interpersonal relationship. A further study is planned to address this issue in the near future.

7. CONCLUSION

This paper has focused on the physical transformability of surfaces, which, among other characteristics, distinguishes OUIs from traditional user interfaces (Holman and Vertegaal, 2008; Parkes *et al.*, 2008). We developed the 'MoleBot' on the basis of the physical transformability of surfaces and implemented kinetic interaction scenarios using a joystick or gestural commands via *Kinect*. User study sessions with the 'MoleBot' prototype and FGI with video scenarios were conducted to understand how people accept the OUI-based robot in their ludic activities and to explore its potential applications.

In the user study session with 12 girls and boys, the participants displayed a few different types of activities: (1) enjoying simple ludic experience, (2) competing in skills, (3) mimicking real-world sports and (4) playing with a companion. According to Caillois' model (Salen and Zimmerman, 2004), competing in skills belongs to agon activities. On the other hand, mimicking real-world spots and playing with a companion are categorized into mimicry activities. The participants also tended to enjoy simple ludic experience with the 'MoleBot'. The experience seemed to be far less intense than ilinx activities and as spontaneous as paidia activities in the Caillois' model. In addition, the playfulness of the experience may be attributed to the fluid physical transformability of the 'MoleBot'. Other results from the user study indicate that two-person groups displayed more active engagement and creative activities than one-person and three-person groups. Participants preferred to control the 'MoleBot' with a joystick, rather than using gestural commands, and they had a tendency to regard the 'MoleBot' as a controllable entity rather than an autonomous creature. From the FGI, the participants suggested that interactive tangible objects, small robots or visual augmentations can be employed to the 'MoleBot' table to enhance user experience through richer kinetic interactions. From the experience of the implementation process and the empirical studies, we found that the idea of 'MoleBot' in the future can evolve into an interactive gaming table or a kinetically informative tabletop.

The 'MoleBot' table involves more than 15,000 physical pixels, so that it provides a compelling sensual experience and enables playful kinetic interactions with physical objects. But as some participants pointed out, it has limited expressiveness because of its unique actuation mechanism. Further studies should be conducted to improve the kinetic expressiveness of the 'MoleBot' and to embody potential application ideas.

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