Journal on Multimodal User Interfaces
https://doi.org/10.1007/s12193-021-00370-2

ORIGINAL PAPER

RFID-based tangible and touch tabletop for dual reality in crisis management context

Walid Merrad[1] · **Alexis Héloir**[1] · **Christophe Kolski**[1] · **Antonio Krüger**[2]

Received: 9 March 2020 / Accepted: 16 February 2021

Abstract

Robots are becoming more and more present in many domains of our daily lives. Their usage encompasses industry, home automation, space exploration, and military operations. Robots can also be used in crisis management situations, where it is impossible to access or dangerous to send humans into the intervention area. The present work compares users' performances on tangible and on touch user interfaces, for a crisis management application on tabletop. The studied task consists of remotely controlling robots in a simulated disaster/intervention area using a tabletop equipped with a layer of RFID antennas, by displacing mini-robots on its surface matching the situation of the real robots on the ground. Dual reality enforces an accurate and up-to-date mapping between the real robots and the mini robots on the tabletop surface. Our findings show that tangible interaction outperforms touch interaction in effectiveness, efficiency and usability, in a task of remote control of one and two robots; only when the user manipulates a single robot remains the efficiency dimension unchanged between tangible and touch interaction. Results also show that tangible interaction technique does not significantly lower the users' workload. We finally expose a post-experiment interview and questionnaire results, assessing the participants' overall satisfaction and agreement on using tangible objects on a tabletop.

Keywords Tangible interaction · Touch interaction · Tabletop · Dual reality · Crisis management · Robots

1 Introduction

Recently robots are increasingly helping humans achieve and complete difficult tasks, across a wide range of usages and particularly in hostile environments [1–4]. They assist firefighters and rescuers in their duties, as current technologies permit remote control, visualization, and monitoring of their environment. Crisis management might require to explore an uncertain or dangerous environment such as a nuclear disaster site or a collapsed building. In such environment, it is dangerous for humans to interfere and robots can prove useful. Therefore, researchers have developed several applications and methods to remotely control mobile robots, using joysticks like in [5] or using computer mouse like for instance in [6–8]. The intervention area's plan/map is often known and available for persons intervening, i.e. firefighters or rescuers, and is used to better locate the robots while moving in and exploring the area. In this context, using a tabletop offers a small-scaled bird's-eye view on the intervention area; mini graphical or physical robots can be placed on the tabletop surface to represent the real robots, and hence establish a virtual counterpart of the intervention area. A network mapping is needed for communication, which could be via Wi-Fi, xBee like in [6–8], or other wireless communications. Our main contribution in this work consists of comparing tangible and touch interaction techniques on tabletop, in a dual reality setup as defined in [9,10], for tasks of remotely moving robots and exploring a disaster zone. First we present a study which measures users' performances. Then we provide results in terms of effectiveness, efficiency, and usability. We also highlight the differences between these two interaction techniques and we compare them on each metric of the ISO/IEC 9126-4 norm.

Generally speaking, this work contributes to the design and evaluation of multimodal user interfaces, by using phys-

✉ Christophe Kolski
christophe.kolski@uphf.fr

Walid Merrad
walid.merrad@uphf.fr

[1] LAMIH CNRS UMR 8201, Univ. Polytechnique Hauts-de-France, Valenciennes, France

[2] DFKI, Saarland Informatics Campus, 66123 Saarbrücken, Germany

ical (tangible) and virtual (graphical) objects on an interactive tabletop surface. This tabletop can detect and trace tangible objects on its surface by the mean of RFID technology. It is indeed equipped with RFID antennas; and objects are labeled with RFID tags, thus it is possible to couple them with virtual displays on the screen of the tabletop and consequently act as needed. Meanwhile virtual objects are displayed graphically on the tabletop's screen; this latter allows also users to interact with them. The interaction on the tabletop surface can be supported by both tangible and touch. We note that we have previously carried out a research [11] that this present work is based on and constitutes an extension of it. We present an extended bibliography and an extended description of the background, we fully expose and illustrate the application and our detailed study design. We also present findings that were not exposed or detailed in our previous work.

This article is organized as follows: in Sect. 2 we expose definitions and state of the art of concepts related to dual reality, touch interaction, tangible interaction and human-robot collaboration. We also give a brief review of tabletops as they account for our interaction support. In Sect. 3 we present our study design along with participants' details, apparatus and our software application, tasks and scenarios. Section 4 illustrates our findings, divided into two main parts. In Sect. 5 we discuss our findings and highlight recommendations for applications designers. Finally, Sect. 6 concludes this work, highlights possible improvements and shows our perspectives.

2 Background

In this Section, we introduce the state of the art and we provide a definition of dual reality, touch interaction, tangible interaction and human-robot collaboration.

2.1 Dual reality

2.1.1 Definition

Lifton in his PhD thesis [10] defined the concept of dual reality as "an environment resulting from the interplay between the real world and the virtual world, as mediated by networks of sensors and actuators. While both worlds are complete into themselves, they are also enriched by their ability to mutually reflect, influence, and merge into one another". He states that "sensor networks will turn the physical world into a palette, virtual worlds will provide the canvas on which the palette is used, and the mappings between the two are what will make their combination, dual reality, an art rather than an exact science. Of course, dual reality media will in no way replace other forms of media, but rather complement them".

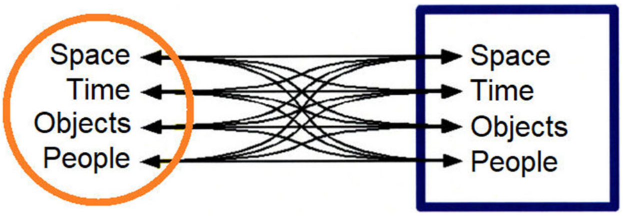

Fig. 1 Fundamental mappings between the real (left) and the virtual (right). Adapted from [10]

Furthermore, he adds that "a complete consideration of dual reality must also include the possibility of *sensor* data from the virtual world embodied in the real world. Insofar as technically feasible, dual reality is bi-directional". According to Lifton, a direct mapping between the two worlds (mapping of the real to virtual and vice-versa) maybe not be the most appropriate in all situations. Hence he proposes a mapping strategy shaping the virtual world according to our subjective perceptions of the real world (see Fig. 1), whereas Fig. 2 shows a comparison of dual reality and the real-virtual axis.

Lifton and Paradiso added that both worlds are enhanced by the ability to mutually reflect, influence, and merge by means of sensor/actuator networks deeply embedded in everyday environments [9]. In this same paper and to pursue with the idea, they presented a system made under the Dual Reality paradigm: by a plug sensor node, the system demonstrates the information flow from the real world to a virtual environment, this latter one is implemented in the *Second Life Online Virtual World*[1] [12,13], where the data sensed from a real object (such as light, temperature, motion, sound and electrical current) influences the corresponding digital representation.

2.1.2 Application domains of dual reality and implementation examples

We expose here some examples of dual reality applications; they are diverse and they express different objectives.

Example 1 The dual reality concept can be applied to different domains. For instance, managing a factory as demonstrated in [14] is a good example, where Back et al. have designed a virtual factory that reflects a real world chocolate factory [15] located in San Francisco, USA. Data is collected and imported, by means of sensors implanted in the real factory, to the virtual environment where several users can do simulations, visualizations and collaborate using a set of interlinked, real-time layers of information. Figure 3 shows the virtual (left) and the real (right) environments. Furthermore, these authors developed mobile and web-based

---

[1] Still accessible on 09-16-2019.

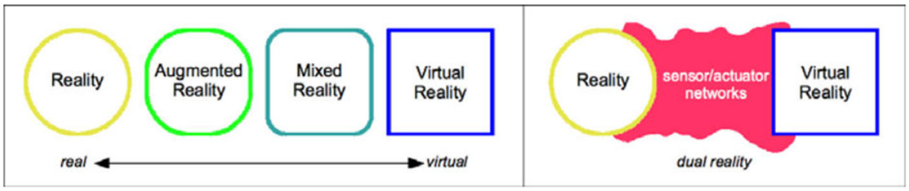

Fig. 2 An environmental taxonomy as viewed on the real-virtual axis (left). Sensor networks seamlessly merge real and virtual to form dual reality (right) [9]

Fig. 3 **a** An avatar in the multiverse virtual factory. **b** The Tcho factory floor under construction. Adapted from [14]

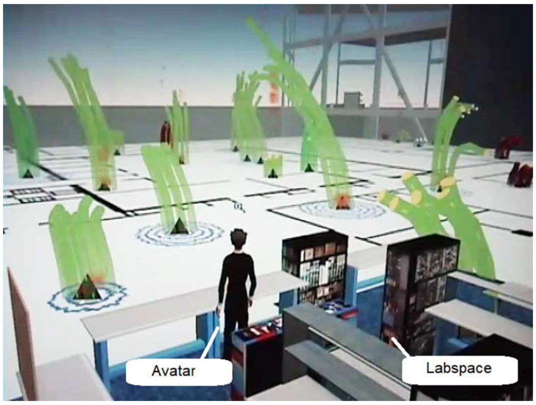

Fig. 4 Side view of the final implementation of Shadow Lab, which includes data ponds; adapted from [9]

collaboration environments, that could be used simultaneously and interchangeably, allowing users to collaborate distantly in industrial settings, such as factories in one country and managers in another one.

Example 2 In [9] Lifton and Paradiso have showed another example called "Shadow Lab", which is a virtual space in *Second Life* that reflects a real lab. The real lab has the Plug sensor network [10,16,17] deployed; it exemplifies their real space to virtual space mapping. Figure 4 shows the implementation of "Shadow Lab" where an avatar is standing; their labspace –in the foreground– is rendered in detail while the rest of the building –like in the background– was represented by a map.

The authors state that "The primary feature of Shadow Lab is the to-scale two-dimensional floor plan of the third floor of our building. Only a small portion of the entire space is modeled in three dimensions. In part, this is due to the difficulty and resource drain of modeling everything in three dimensions" [9]. Figure 4 shows the map of the lab in the virtual space (Shadow Lab), with approximately 30 data ponds. These data ponds are placed accordingly to their positions of their corresponding plugs in the real lab [9], demonstrating the dual reality paradigm.

Example 3 In this example [18], the realistic task of "shelf planning" from retail domain is replicated in a virtual world. This is a daily task that is being performed in retail stores in order to optimize the profit, which consists of ordering and positioning the products in a shelf. A real and a virtual environment have been designed where users can place real and virtual products at desired positions on shelves. The influence is mutual between the two environments, which are kept always "synchronized".

In a complete dual reality setup, if a product placement is done in one side (virtual or real) it should be automatically replicated in the other side (real or virtual, respectively). To workaround this automation in the experimental setup, a hidden –person– assistant ensures the work of a robot grabbing and placing tangible products in the shelves according to the virtual counterpart. This dual reality setup was part of a study comparing the efficiency of dual reality, its performance and its task solution strategies to virtual and real setups (see Fig. 5).

In this same context of retail, Kahl et al. [19] have worked on a virtual dashboard that offers a real time visualization of an actual supermarket in an interactive 3D model, including simulators and communication channel between the two worlds. It reflects changes in the real world instantly to the virtual world, and information from the virtual world are also interpreted in the real world. This work in linked to the living

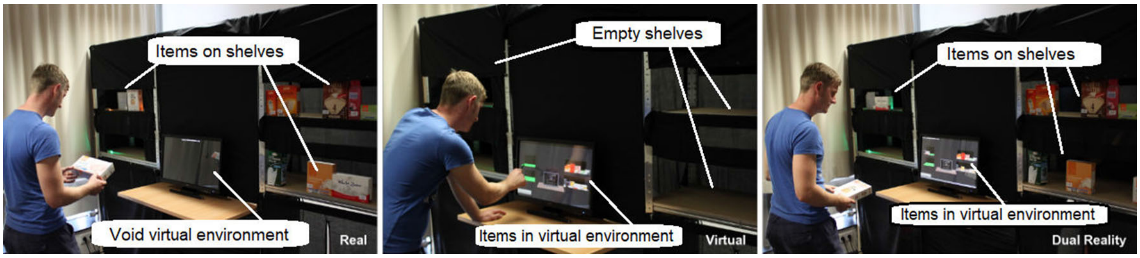

Fig. 5 Environment in the real, virtual and dual reality condition. Adapted from [18]

lab project *Innovative Retail Laboratory* [20] of the DFKI[2] in collaboration with German retailer *GLOBUS SB-Warenhaus Holding* in St. Wendel.

Another similar work in the domain of retail is that of Khan et al. [21], which consists of a virtual supermarket. A user can interact with this environment by moving his/her head since the virtual scene follows the orientation of the user's head. A shortcoming of this system is that is uni-directional, hence it does not fit into the dual reality paradigm.

Although all these examples and others shown in [22] and explained from a dual reality perspective, also using tabletops such as [23–25], there has been no work related to remote control of mobile robots in a dual reality setup.

2.2 Touch interaction

Nowadays multi-touch user interfaces are pervasive and ubiquitous, thanks to the different interaction styles with the surface(s) they offer and the degrees of freedom made available to users when interacting with the surface(s) [26–29]. Several researches and studies have been carried out about multi-touch interaction technique on different aspects. For instance we can cite studies about user performances and preferences of different fingers and chords for pointing, dragging and object transformation [30], the effect of touch latency on one-handed and two-handed (respectively elementary and composite) tasks [31], users' consistency in gesture production [32] and the versatility of multi-touch gestures [26,27]. Other studies such as [28,33] which are about the users' perceived difficulty of multi-touch symbolic gesture articulation, analyzed from different perspectives of number of fingers, number of strokes and number of hands and their synchronicity. Another study [34] is about users' attention demand of touch and tangible interaction on a composite task, and [35,36] dealing with people with motor impairments making gestures articulated on touchscreens. The study of Tuddenham [37] shows negative results of bimanualism for touch interaction even though it was possible to use both hands, while another study [38] shows positive results of bimanualism on tabletops, using touch interaction technique. There could be many factors affecting this, particularly the nature of the task and the system design.

A study shows that in some cases users do not use bimanualism with neither tangible nor touch interaction [37] even though it is possible to use both hands; while other studies report positive results for bimanualism in both tangible [39] and multi-touch [38] interactions on tabletops. There could be many factors affecting this difference, notably the design of the system and the nature of the task. In [28,34], Rekik et al. have outlined several touch interaction design guidelines for tabletop design, gesture and hands synchronicity ergonomics. Other guidelines have been outlined related to ease of learning and recalling [40–42], ease of execution [29, 43], gesture set design [28,29], gesture recognizer [28] and well fit to application functions [29,42]. To our knowledge, there is no study that has highlighted guidelines and recommendations related to mobile robots remote control using a tabletop, except Kato et al. [44] who discussed the *top-down view* and the *focus on field* aspects, which is related to the ceiling camera they use. However, this lacks recommendations and guidelines regarding the use of touch interaction.

2.3 Tangible interaction

Tangible User Interfaces (TUIs) bridge the physical world and the digital world together by manipulating physical artifacts (known also as tangible objects) in order to interact with digital representations [45–47]. These artifacts are used for representations and for controls at the same time, they can be static like in [39] or dynamic like in [48]. Dynamic tangible objects are mobile and usually equipped with motor(s), sensor(s), screen(s), etc.

TUIs systems can be implemented on different material supports. For instance, one can cite interactive surfaces whose applications, among many, are the control of robots [11,49–51], the creation and edition of music [23, 52], education and learning [24,53–56]. Interactive surfaces encompass interactive walls (vertical support) such as the work of Detken et al. [57] and Buur et al. [58]. They also include tabletops which are –horizontal– interactive displays emphasizing collaboration, planning, organizing,

---

[2] German Research Center for Artificial Intelligence. Website: www.dfki.de.

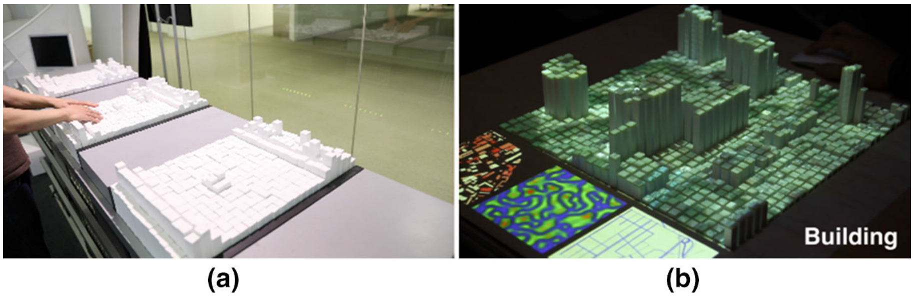

Fig. 6 Shape-changing interfaces. **a** Conjure interface [74]. **b** Tangible CityScape interface incarnating buildings [75]

Fig. 7 Tangible user interfaces (upper picture) and their corresponding robots (lower picture) [50]

and other spatially-situated activities [59–61]; characteristics well-suited to the task of orchestrating a team of robots. Among the technologies used for capturing objects on these tabletops are RFID like in [62–64], camera-based detection like in [65], acoustic and infrared like in Tviews [66], fiber and optical like in [67,68] and light sensors like in [69]. For more examples and details about capture technologies, the reader is referred to the thesis of Kubicki [70]. There exist other supports such as shape-changing user interfaces and transformable shapes, which change their topology so that users can feel and manipulate data with their hands and body. Researches and works in this context have been done by Nakagaki and his colleagues in MIT.[3] Some of their works are "inForce" [71], "Materiable" [72], "SoundFORM" [73], "Conjure" [74] (see Fig. 6 (a)), "Tangible CityScape" [75] (see Fig. 6 (b)), "Physical Telepresence" [76,77] and "Programmable Droplets for Interaction" [78,79]. Robots and mobile devices [80–84], and shape-changing objects [83,85–87] can be both used as tangible interaction mediums.

Different benefits of TUIs have been shown in several user studies and researches; these benefits include natural affordances of tangible objects [88], bimanualism [89], enjoyment and programming self-beliefs [84], positive impact on learning such as in [84,90–92] and various aspects of embodiment [45]. Through these TUIs studies and others, researchers have outlined several guidelines assisting practitioners in different aspects of design. Among these guidelines are the ones related to better collaborating [55,93], to learning [88,91,92] and to better illustrate the information [76, 94,95]. Other studies have also shown that TUIs enhance the level of engagement of users, facilitate exploration, and promote action and interaction [96], enhance performance in a problem-solving activity [55], improve the user experience during manipulation tasks [97–99], and offer accessible interaction design for people with impairment [100,101]. A study shows that, like for touch interaction, in some cases users do not use bimanualism in tangible interaction [37] even though it is possible to use both hands, while another study reports positive results for bimanualism in tangible interaction on tabletops [39]. Like for touch interaction, this could be affected by many factors, including the design of the system and the nature of tasks. We briefly note that TUIs outperformed multi-touch interfaces in many tasks like acquisition/manipulation [37], layout manipulation [102], grouping [103] and sorting [39]. In this context and taking into consideration the benefits of TUIs mentioned above, we investigate the human-robot collaboration on tangible and touch tabletop surface, with tasks related to remote control of mobile robots. Under pressure, we expect that differences between our TUI and touch user interface are significant in favor of TUIs.

2.4 Human–Robot collaboration

Many Human-Robot collaboration and cooperation studies have been done with other supports than tabletops. Studies like [6–8] use a computer with screen to visualize the robot(s) position(s) and its mouse to point destinations that robot(s) should reach. Other studies such as [5] use a screen for visualization and a joystick for controlling the robot(s) remotely. Only few studies in this matter have been done with table-

---

[3] Massachusetts Institute of Technology; www.mit.edu.

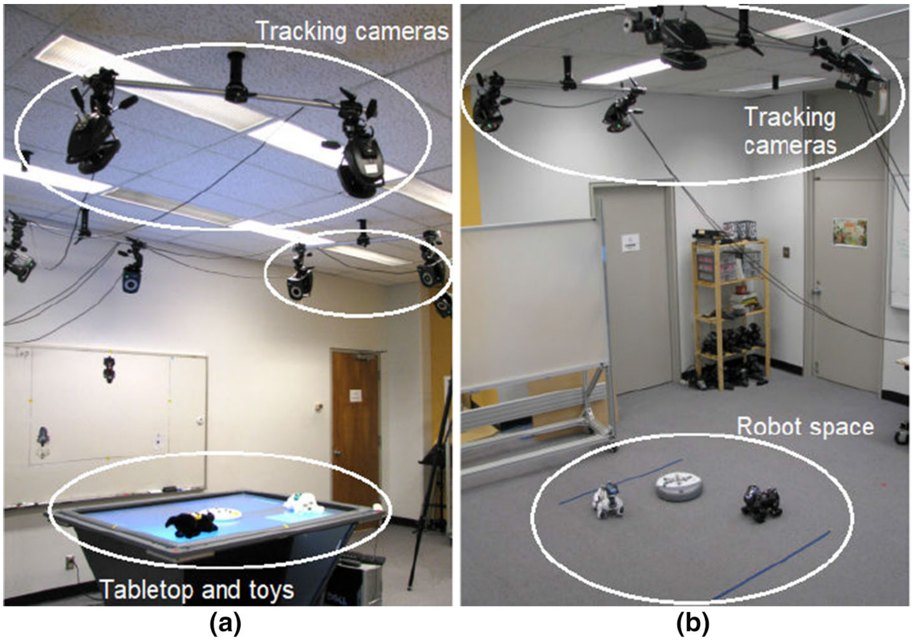

Fig. 8 **a** The tabletop workspace with the TUIs on top and the Vicon ceiling setup [50]. **b** The robot workspace with Vicon cameras and robots [50]

tops. For instance, Guo et al. designed a system where it is possible to manipulate robots using a TUI [49,50], through a tabletop and physical toys as counterpart of robots on the ground, Fig. 7 shows the TUI and the corresponding robots.

In this study, a mapping between the toys on the tabletop and the robot space is established using two multi-camera systems, one is used to track the robots space and the other one to track the toys on the tabletop surface (see Fig. 8). When users interact with the toy (respectively toys) on the tabletop, the corresponding robot (respectively robots) on the ground will move to its (respectively their) new position (respectively positions). However, this system has no real time feedback from the robot(s) to the user(s). The results indicate that TUIs outperformed touch interface in usability and in precise control over robot movement. The results also revealed that TUIs make it easier to move the robot to the target location and rotate the robot as required, when compared to touch, with different scores between one, two and three robots. Furthermore, the users tend to prefer TUIs over touch when the number of robots increases. Although, this study does not reveal any measures about the users' workload. Other human-robot interaction researches have been carried out to study multimodal feedback in outdoor multi-robot teleoperation such as [104]; the impact of human–robot multimodal communication on mental workload and usability preference such as in [105]; and the differences between older and young people on using multi-modal human–robot interfaces such as in [106].

The study presented in [11] empirically compares tangible interaction with touch interaction on tabletops in a dual reality context. The study consisted of remotely steering one and two robots in order to explore a simulated disaster area. A tabletop capable of displaying a graphical representation of the robots as well as handling the tangible proxies of the robots provided the underlying interaction mechanics. Results indicated that the TUI outperformed touch interface in usability (which was measured using SUS questionnaire) and users made fewer errors when using TUI than when using touch interface. Meanwhile, the users' workload showed a non-significant difference between TUI and touch interface. Another example is the work of Kato et al. [44], a multi-touch interface system is developed for controlling multiple robots and it relies on ceiling-mounted cameras. These latter help with tracking the mobile robots on the ground when users displace them, by manipulating corresponding images of robots on the surface of the tabletop. Regarding data transmission, we highlight that the ITU-T [107] has the potential to facilitate the establishment of standardized dual-reality capable communication channels between the exploratory robots and the novel human-machine interaction solutions.

2.5 Synthesis

We have presented in this section the background of our study. We have been through the different related work in each domain. As we mentioned previously, to our knowledge, there has been no study that highlights in depth mobile robots remote control using a tabletop with touch and with tangible interactions, except the study of Guo et al. [49,50] that we presented in Sect. 2.4. This latter lacks the real time feedback from the robot(s) to the user(s) and it cannot be implemented in real life scenarios because of the tracking cameras. Furthermore, this study does not investigate the users workload. None of the works mentioned does exactly what is being done

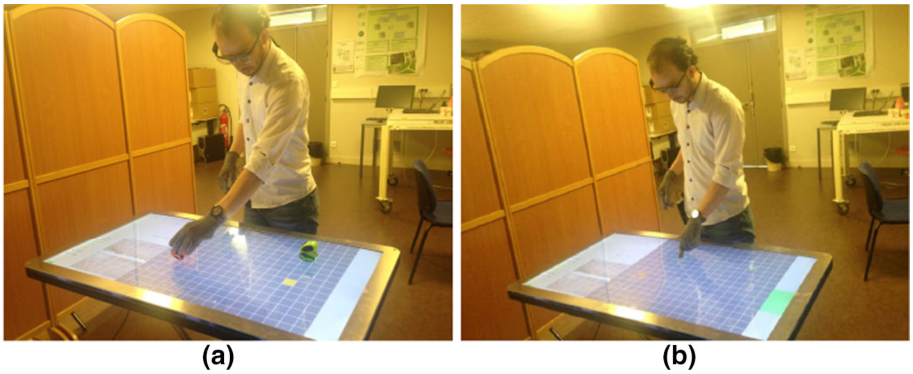
(a) (b)

Fig. 9 **a** The tangible version of the application the Tangisense Tabletop. **b** The touch version of the application the Tangisense Tabletop

in the present paper. Given this background and our motivations, our study reflects a real life intervention of firefighters for crisis management in a hazardous environment, hence the need of using robots and the actual material installation. We describe in details in the next Section our study design through four steps: apparatus and software application, tasks, scenarios and participants.

3 Research question and study design

The purpose of this study is to investigate and understand the benefits of tangible interaction, in a dual reality setup, when interacting with the virtual side of a dual reality to affect the real side. It principally focuses on evaluating the users' workload and the usability of the system.

3.1 Apparatus and software application

We have developed an application using Java on the TangiSense tabletop [4] [108] for crisis management which offers two different interaction modalities: tangible interaction and touch interaction. The application has the same functionalities, same design and same physical support (tabletop), the only difference is within the interaction modality. Both tangible and touch versions of the application operate in a dual reality setup, where the virtual side is composed of the tabletop –hence the intervention map– together with objects (tangible and graphical) laying or displayed on the tabletop surface, while the real side is the intervention field, the real robots on the ground and the supposed victims. The setup of our study is that the tabletop and the -toy- robots reflect the real intervention area, via a video feedback and robots' location feedback. It is therefore possible to reflect the current actual locations of the real mobile robots on the map in real-time, since the tangible objects on the tabletop surface can move by themselves such as in [109].

The TangiSense 2 tabletop used in this study is set on a display resolution of 1920 × 1080. It is equipped with a 47″ screen of 90 cm × 60 cm display surface. The tabletop capture technology is based on RFID technology to detect tangible objects on its surface (see [54] for more details); its sensing capacity is measured by the number of RFID antennas on its surface, it is of 16 × 24 objects at the same time, corresponding to 16 × 24 –square– RFID antennas of 3.75 cm long each, working on a frequency of 13.56 MHz. Finally, the tabletop is connected to a computer running Windows 10 (see Fig. 14).

Each physical (dynamic or static) object used on the surface of the tabletop is equipped with an RFID tag (see Fig. 12b). The antennas of the tags are such that they can be read (or captured) from a single Tangisense antenna at once. The tags are round-shaped and measures 3.2 cm of diameter. For the touch feature on this tabletop, we use a glove for the right hand and another glove for the left hand, each one of them is equipped with an RFID tag in the index finger (same RFID tag characteristics as the tangible objects' ones). Thus, the gloves are used to simulate a touch interaction feature with the tangible tabletop surface (see Figs. 9b and 10). Furthermore, participants were required to wear the gloves during the whole experiment to guarantee the same conditions in both systems, even if the gloves were deactivated in the tangible version. In order to keep the same precision for the two interaction modalities, for the task to be performed, it was necessary to keep the same technology by simulating the touch modality. We combine the two modalities (tangible and touch) with the possibility of exploiting a large number of objects simultaneously, which offers great precision in terms of positioning of each object on the tabletop surface. We note that due to technical limitations, it is necessary to proceed to simplifications in the task, and make it in a way to have tasks with rectilinear displacements, stops and restarts of the moving objects on the tabletop (and thus the same with the robots on the simulated field).

To command the real robots on the ground and to interact with the system in the tangible version, participants use the tangible mini-robots and displace them on the surface of the

---

[4] The tabletop was designed by Rfidées company: www.rfidees.com.

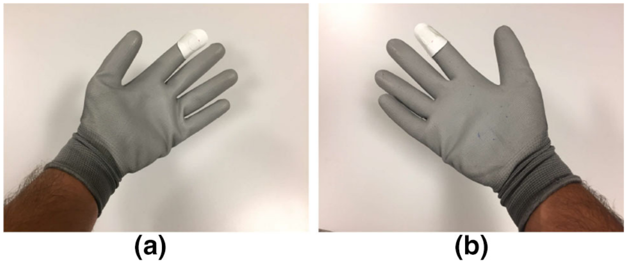

Fig. 10 The gloves that simulate the touch feature on the tabletop, with the RFID tags in the index fingers. **a** The left hand glove. **b** The right hand glove

tabletop. Whilst in the touch version, graphical representations are used as counterpart of the real robots on the ground; and to interact with the system participants tap on the screen to select objects and to point destinations. We also suppose that we previously know the intervention field map and we represent the supposed disaster area on a small scale on the tabletop (see Fig. 9). Possible situations and types of disasters where our application could be used and helpful are shown in Fig. 11, all of these types have a common principle which is the potential usage of robots to explore the area during the intervention.

We use the Lego Mindstorms NXT (Fig. 13a) platform to design and build the robots on the ground. The platform is low cost and enables fast prototyping of small robots. The platform accepts several programming languages; we used *RobotC*. The embedded program let the robots to navigate autonomously from their current locations to given destination(s) based on a Model Predictive Control (MPC) framework, which is a model for the limited capacity of this type of robots. More details about the MPC algorithm can be found in the works of Habib et al. [7] and Marzat et al. [113]. We use XBee wireless communication to send and receive data and desired/actual positions of robots from and to a dedicated computer (PC2 in Fig. 14), i.e. only in the real side of dual reality. As the locations of the tabletop and the robots are geographically distanced, we ensure the communication between them using a wireless LAN (Wi-Fi). Furthermore, each robot is equipped with a smartphone camera which stream the robots surroundings. Figure 14 shows the global system architecture, the communications and how we collect data for the experiment, where the green flows express data from cameras installed on the experiment areas, blue flows express user answers to questionnaires and red flow express the experimenter remarks and notes. More details about the data and their origins can be found in Table 1.

The context of this application is similar to the work of Habib et al. [8], which is in the domain of crisis management with firefighters, where a human operator is in a command post (in our case it is represented by the virtual world of dual reality and the tabletop) and robots operate in a hostile environment (in our case it is the intervention area/real world). The hypothesis behind this study were the followings:

H1. The TUI has a higher usability score than the touch user interface.
H2. Users workload using the TUI is lower than when using the touch user interface.
H3. Users make less errors during their trials using the TUI than using the touch user interface.

3.2 Tasks

In this study, participants were asked to perform two main tasks, both of them are about controlling robots remotely using the tabletop:

1. The first one consists of controlling remotely one robot, moving it from point A (its current location) to point B (a predefined destination shown on the tabletop surface); Fig. 15a illustrates this first task setup on the tabletop (tangible version).
2. The second one consists of remotely controlling two robots at the same time, taking them from point A_1 and A_2 (their current locations) to point B_1 and B_2 respectively (their predefined destinations shown on the tabletop surface); Fig. 15b illustrates this second task setup on the tabletop (tangible version).

As a secondary task and as we believe this will increase the participants workload, participants were required to explore the intervention field, by the mean of a live video feedback using the cameras installed on each mobile robot, and to capture pictures of the situation around supposed victims on the ground, all this while the robot (respectively robots) is (respectively are) moving to its (respectively their) destination(s). Figure 16 shows an example of a user manipulating a –second– robot (through a tangible toy) while exploring the disaster area and taking pictures of supposed victims. The number of victims on the ground is the same as the number of robots used, i.e., one victim when using one robot and two victims when using two robots. Each victim is discoverable by only one robot camera whom trajectory passes nearby its location, making it possible to be seen by the camera.

When using the tangible interface, participants can control robots by manipulating the mini-robots (Fig. 12) with their hands and place them on the desired or predefined destinations on the tabletop surface (on the map of the intervention field). In order to take photos of supposed victims, participants use a camera tangible object and place it on the corresponding video frame of the desired robot (see Fig. 13b). The picture is taken at that instant of the video. While in the touch interface version of the application, participants use their –index– fingers on the tabletop surface to select the –

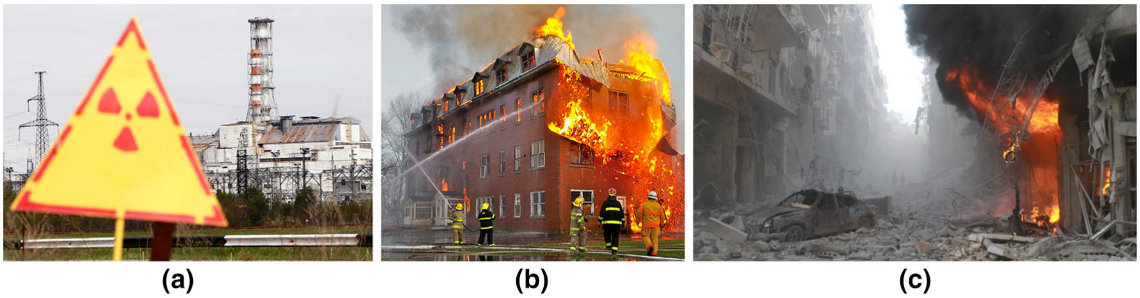

Fig. 11 Possible types of disaster where our system could be used. **a** Contaminated zones [110]. **b** Fire zones [111]. **c** battlefields; adapted from [112]

Fig. 12 **a** Mini-robot toy used on the tabletop surface, equipped with RFID tags. **b** The RFID tag sticked to the mini-robot from below, used on the tabletop surface

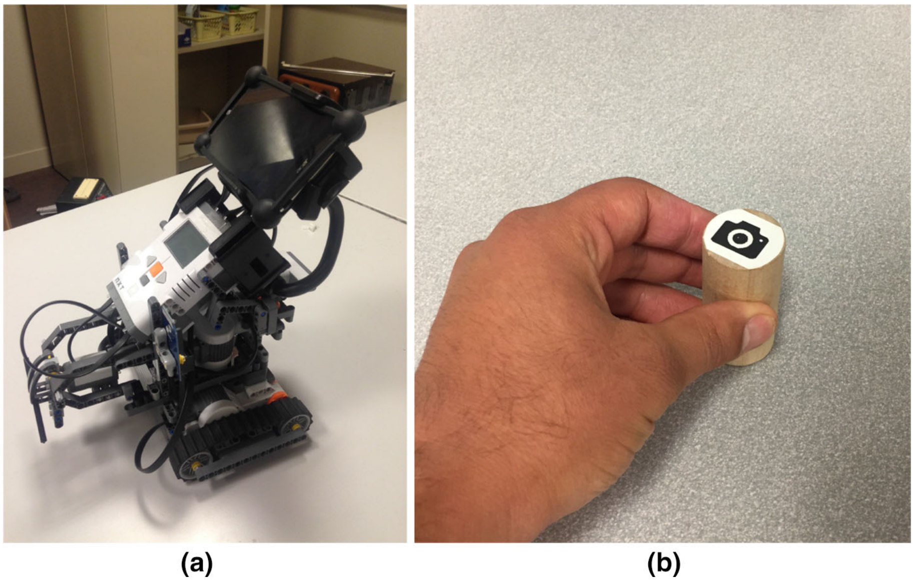

Fig. 13 **a** Lego mindstorms NXT robot equipped with a camera. **b** The camera tangible object used to take photos in the tangible interface version of the application

graphical– robot they want to interact with, then point out the destination location. To take a picture of a supposed victim in this version, participants select (directly, with no need to previously select the robot) the video frame of the desired robot and tap on the camera icon. The picture is taken at that instant of the video.

In order to make all of these tasks and the scenario more demanding and more stressful while using two robots, participants are instructed to manipulate the second robot (thus consequently explore the field and picture supposed victims' surroundings) simultaneously to when exploring the field and taking photos using the first robot, hence using the two hands in parallel. The instant to start displacing a robot is given by a colorful signal, flashing for few seconds on the left side of the tabletop, where each colour of a signal refers to the same colour of robot to move; i.e. green signal flashing means move the green robot and orange signal flashing means move the orange robot.

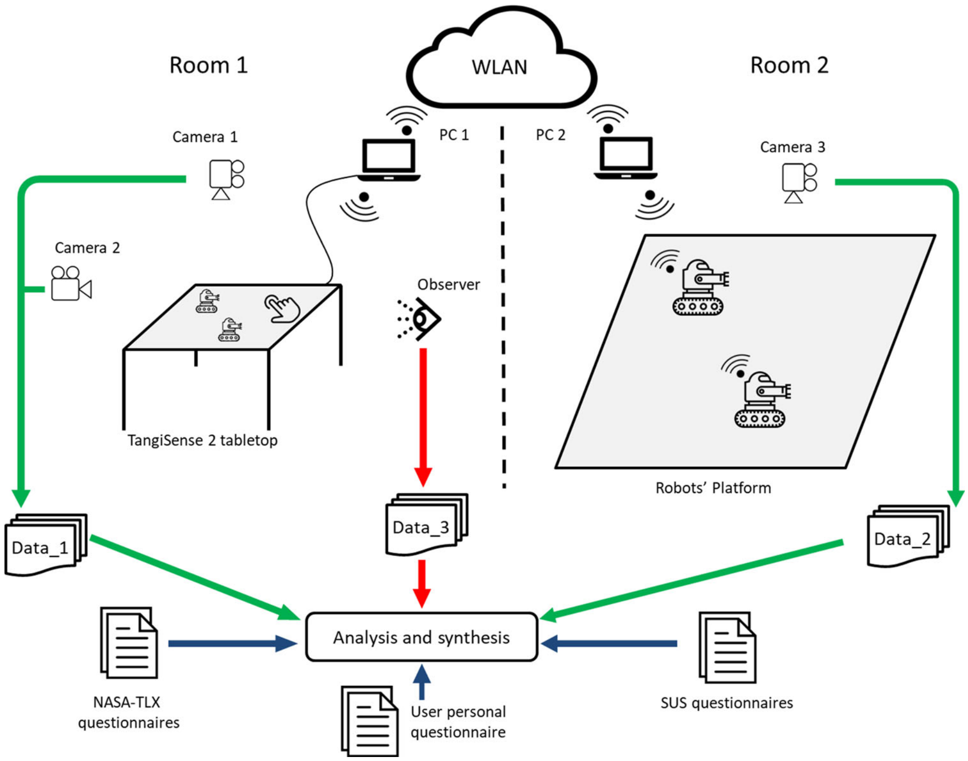

Fig. 14 Global architecture of the system and data flow

Table 1 Data descriptions and their origins

Data	Description	Origins
Data_1	The beginning of a task (timing)	Camera 1 and camera 2
	Errors and their categories	
Data_2	The end of tasks (Timing)	Camera 3
Data_3	Completion of tasks	The observer's (experimenter)
	Errors and their categories	Notes and evaluation
	Potential remarks	
NASA-TLX questionnaires	Participants' answers to questions	NASA-TLX questionnaires
	Related to workload	After finishing each task
SUS questionnaires	Participants' answers to questions	SUS questionnaires, after finishing
	Related to system usability	Performances on each system
Participant personal	Participants' personal data	Questionnaires given to participants
Questionnaire	Previous knowledge on tabletops and robots control	In the beginning of the experiment

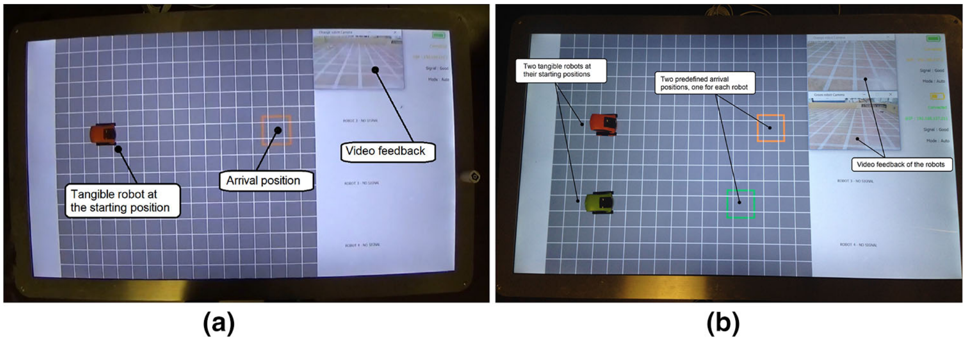

Fig. 15 **a** Task one illustrated (using one robot). **b** Task two illustrated (using two robots)

Fig. 16 A participant performing with two tangible robots, exploring the disaster area and taking pictures of supposed victims

The signal to start moving the first robot is given after 5 seconds of the application launch. We judge that it is enough time for participants to be ready for the manipulations. Each colorful signal lasts blinking for 7 seconds; therefore, the signal to start moving the second robot (in case of using two) is given 7 seconds after the first signal. This time lapse of 7 seconds was determined by the following constraints:

- The second signal to move the second robot has to be while the user is already manipulating the first robot.
- There should be enough blinking times for the user to notice it.

3.3 Scenarios

When participants come for the experiment and first of all, they are asked to fill in a pre-experiment questionnaire, consisting of their personal information and previous knowledge on tabletops and tangible interaction (see Appendix A.1). Then, participants get explanations about the functioning of the whole system, the tabletop application interfaces (tangible and touch), the usage of tangible objects and the principle behind the RFID technology. Participant were asked to try both versions of the application and get familiar with them, questions were encouraged in this phase in order to make everything clear about the experiment. After this phase and to avoid any misunderstanding of using the system in its two versions, we briefly tested our participants by asking them to perform some elementary tasks.

Next, we explain the experimentation context and the sequence of tasks. We also explained each task separately before it starts, along with the concerned user interface, tangible objects usage and the potential of using bi-manual interactions on the tabletop surface. Participant are required to complete –the same– two tasks on both system interfaces: one task using one robot and another task using two robots. At the end of the experiment, every participant has performed a total of four tasks, whose sequence is counterbalanced between the two interfaces and the two tasks. We highlight that the tasks' order is the same in the two conditions (interfaces), i.e., a participant who starts performing on one interface –whether tangible or touch– with one robot (respectively two robots), will start performing with one robot (respectively two robots) on the other interface. See Fig. 20 in Appendix B which summarizes the whole scenario and sequences.

To evaluate the participants' workload, they fill a NASA-TLX questionnaire [114] after finishing each task on each interface. The questionnaire assesses each participant's mental demand, physical demand, temporal demand, performance, effort and frustration towards the executed task. To compare the usability of the two applications/systems interfaces, participants answer a System Usability Scale questionnaire (SUS), containing the 10 standard questions [115], after finishing performing on each application interface. The global score of usability is calculated, for each system separately, using the participants' answers to the SUS questionnaire as follows:

1. For each of the odd numbered questions, we subtract 1 from the scores.
2. For each of the even numbered questions, we subtract the given score from 5.
3. We sum together the new values (scores) then we multiply the result by 2.5.

For more details about the SUS questionnaire template, the scales and the score calculation method, the reader is referred to [115]. During the performing, the experimenter observes the participant performance and notes whether the task has been successfully completed or not (1: successfully completed, 0: unsuccessfully completed or uncompleted at all), in addition to manipulation errors and their classifications. At the end of the experiment, participants were asked to complete a post-experiment questionnaire (see Appendix A.2), discuss their experiences with the experimenter, share their remarks and make suggestions if they had any.

3.4 Participants

32 participants (9 female, 23 male) have been recruited in this study, mostly Ph.D. students in our lab and undergraduates with different scientific majors. Their ages ranged from 22 to 39 years old, with an average age of $M = 27.97$ and $SD = 4.28$. All participants were right-handed, all with nor-

mal or corrected to normal vision and all having normal arm mobility, none of them had any kind of disability. Participants were instructed as follows: (1) Participants can use one or two hands at once while interacting with different objects and/or performing different tasks. (2) In case of using only one hand, it is preferred to use the dominant hand during the whole experiment trials. If a participant is more comfortable using his/her non-dominant hand he/she can use it. (3) In case of using only one hand, the participant must use the same hand while performing on TUI and on touch interface, whether it is the dominant hand or the non-dominant one. (4) Every participant must go through both versions of the application (tangible and touch) in a given order by the experimenter, as the study was design as a repeated measure.

4 Results

The outcomes of this study spans over two dimensions: the first one is in accordance with ISO/IEC 9126-4 standard [116], which recommends that to evaluate the usability of a system we should include *Effectiveness*, *Efficiency* and *Satisfaction*. The second one is post experiment interviews and users' self-reported evaluations to several questionnaires. We provide details on each dimension in the following.

4.1 Criteria from ISO/IEC 9126-4 standard

4.1.1 Effectiveness

This is the accuracy and completeness with which users achieve specified goals. It can be calculated through the following two methods:

- Completion rate: calculated by assigning a binary value of '1' if the participant manages to complete a task and '0' if he/she does not. It can be represented as a percentage using the following equation:

$$Effectiveness = \frac{number\ of\ tasks\ completed\ successfully}{total\ number\ of\ tasks\ undertaken} \times 100\ \%$$

- Number of errors: errors can be unintended actions, slips, mistakes or omissions that a user makes while attempting a task. For each task, an average number of errors is calculated as follows:

$$Average\ number\ of\ errors = \frac{number\ of\ users\ making\ an\ error}{total\ number\ of\ users}$$

It is more convenient to start with the number of errors as some errors may lead to uncompleted tasks. Errors made by participants during their trials are classified into categories along with their description as shown in Table 2.

Table 2 shows that participants always made more errors using touch interface than using tangible interface, given the same number of robots used. Moreover, we notice that the sum of errors made when using one robot (19) is less than half the sum of errors made when using two robots (45). This is coherent with the NASA-TLX outcomes that we describe next, however it requires further investigations to correlate these two metrics together.

Table 3 shows further errors analysis; here also tangible interaction using one robot (respectively two robots) outperforms the touch interaction when using one robot (respectively two robots). For the tasks performed without any mistake, we notice that the difference is bigger when using one robot than when using two robots, the same applies for the average number of errors per task. We believe that this is also related to the users' workloads, we investigate this purpose later in another section.

The completion rates of tasks given in this study are shown in Table 4. We found these results based on the errors made by participants while attempting to perform the tasks (Table 2). As mentioned, we assigned '1' for a completed task and '0' for else. Our results show that the tangible interface outperforms the touch interface only when using two robots, with respectively 78.13% to 68.75%. They also show that both interfaces have the same completion rate of 84.38% when using one robot. Furthermore, we believe that the difference of tasks' completion rates between one robot and two robots, no matter what user interface is used, is due to the user attention and focus, which are better when performing with only one robot. This is also coherent with the workloads outcomes shown previously (significant differences between tasks using one robot and tasks using two robots in the same interface).

4.1.2 Efficiency

Efficiency is defined as the resources expended in relation to the accuracy and completeness with which users achieve goals. It can be calculated in one of the following two ways:

- Time-based efficiency: measured by "goals/unit of time". It is defined by the following equation:

$$Time\ based\ efficiency = \frac{\sum_{j=1}^{R} \sum_{i=1}^{N} \frac{n_{ij}}{t_{ij}}}{NR}$$

Table 2 Errors categories, their description and frequencies

Error category	Description	Number of errors			
		Tangible		Touch	
		1R	2R	1R	2R
Incorrectly placed	An object is not placed by the participant on the right position on the tabletop	0	3	4	2
Not detected	A tangible object is put on the tabletop surface but not detected and not known as present on its surface	0	1	0	0
Wrong object	Participant did not use the right object for a given task. used	2	3	1	0
Wrong robot	Participant did not select or grab the right robot to manipulate selected	0	1	0	2
Missed signal	When participant does not see the flashing signal to start moving a robot	0	7	2	8
Missed photo	When participant does not take a photo of a victim on the ground that has appeared on the video feedback	5	7	5	11
Totals or errors		7	22	12	23

Table 3 Tasks' performed without any mistakes and average number or errors per tasks

Interface	Tangible		Graphical	
Number of robots	One robot	Two robots	One robot	Two robots
Tasks performed without any mistake (%)	84.38	59.38	78.13	56.25
Average number of errors per task	0.19	0.66	0.38	0.72

Table 4 Tasks completion rates by number of robots and by interface type

Number of robots	One robot		Two robots	
Interface	Tangible (%)	Graphical (%)	Tangible (%)	Graphical (%)
Completion rate	84.38	84.38	78.13	68.75

Table 5 Average tasks' completion times and their standard deviations

Number of robots	One robot		Two robots	
Interface	Tangible	Graphical	Tangible	Graphical
Means	24.26	25.3	36.45	40.78
S.D.	2.06	3.89	6.2	6.86

Table 6 Overall relative efficiency results

Interface	Tangible		Graphical	
Number of robots	One robot (%)	Two robots (%)	One robot (%)	Two robots (%)
Detailed	84.39	76.59	84.25	66.06
General	79.7		73.02	

where N is the total number of tasks (goals); R is the number of users; n_{ij} is the result of task i by user j (if the user successfully completes the task, then $n_{ij} = 1$, if not then $n_{ij} = 0$); t_{ij} is the time spent by user j to complete task i, if the task is not successfully completed, then the time is measured till the moment the user quits the task.

- Overall relative efficiency: it uses the ratio of the time taken by the users who successfully completed the task in relation to the total time taken by all users. It can be represented by the following equation:

$$Overall\ relative\ efficiency = \frac{\sum_{j=1}^{R}\sum_{i=1}^{N} n_{ij} \times t_{ij}}{\sum_{j=1}^{R}\sum_{i=1}^{N} t_{ij}} \times 100\ \%$$

where N is the total number of tasks (goals); R is the number of users; n_{ij} is the result of task i by user j (if the user successfully completes the task, then $n_{ij} = 1$, if not then $n_{ij} = 0$); t_{ij} is the time spent by user j to complete task i, if the task is not successfully completed, then the time is measured till the moment the user quits the task.

Table 5 describes the participants timings of each task on each interface; it shows the means and the standard deviations in seconds.

The time-based efficiency is calculated in terms of goals/second. As the average time spent on each task is higher than 24 seconds, the efficiency results would be less than 0.05 goal/second, with small differences and thus hard to compare them. Therefore, we use the overall relative efficiency which is expressed as a percentage, it is easier to understand, compare and spot the differences.

We applied the formula on two different perspectives. The first one to compare tangible to touch interaction techniques, regardless of the task, i.e. number of robots. In this case, the number of tasks is $N = 2$ and it represents the tasks with one and with two robots. The second one as a detailed comparison and taking into consideration the number of robots, here we have $N = 1$ and we apply it to each *interface*× *number of robots* separately; R is always set to 32. Our findings are illustrated in Table 6.

Results in Table 6 indicate that the tangible interaction technique outperforms the touch one, with a score of 79.7% vs 73.02%. This is highly correlated with the completion rates shown previously as this latter uses the tasks' completion scores. When it comes to comparing interaction techniques by number of robots used, we find that for one robot the efficiency is basically the same, 84.39% to tangible vs 84.25% to touch. Contrarily to when using two robots, we notice a considerable difference between tangible and touch interaction techniques (76.59% to tangible vs 66.06% to touch). This may be due to the difference in workloads that we investigate in the next section.

Furthermore, we conducted a *paired t-test* on the tasks' completion times to compare one robot tasks and two robots tasks in both user interfaces. Our findings indicate that there is non-significant difference between tasks using one robot, i.e. $p >> 0.05$, with ($M = 24.26$, $SE = 0.36$) to tangible interface vs ($M = 25.3$, $SE = 0.69$) to touch interface.

4.1.3 Satisfaction

It is about the comfort and acceptability of use of the system. *Standardized satisfaction questionnaires* can be used to measure it after each task and/or after the usage of each system. It is measured in two parts [117]:

- *Task level satisfaction:* this is to measure how difficult is the task that has just been taken. The most popular post-task questionnaires are ASQ (After Scenario Questionnaire), NASA-TLX (NASA's task load index is a measure of mental effort), SMEQ (Subjective Mental Effort Questionnaire), UME (Usability Magnitude Estimation) and SEQ (Single Ease Question) [117]. We use the NASA-TLX questionnaire –for each task– as it is articulated through several sub-scales.
- *Test level satisfaction:* this is to measure the users' impression of the overall ease of use of the two systems. The following questionnaire are widely used in this matter: SUS (System Usability Scale), SUPR-Q (Standardized User Experience Percentile Rank Questionnaire), CSUQ (Computer System Usability Questionnaire), QUIS (Questionnaire For User Interaction Satisfaction) and SUMI (Software Usability Measurement Inventory) [118]. We use SUS questionnaires –for each system– for this purpose.

As we previously mentioned, we evaluate the participants' workload of each task using the NASA-TLX questionnaire. The evaluation was done separately on each sub-scale of this questionnaire. Figure 17 illustrates a workload summary of the four tasks performed, using one and two robots on tangible and touch interfaces, and through the six NASA-TLX sub-scales.

Comparing the tasks with one robot (in tangible and touch), slight differences are found between the sub-scales means (respectively in tangible and touch), in favor of touch interaction only in mental demand and effort. Meanwhile it is in favor of tangible interaction in physical demand, temporal demand and frustration. The performance sub-scale shows an equal outcome between the two interaction techniques. When it comes to tasks with two robots, the gap between the means of each sub-scale is bigger than that of tasks with one robot,

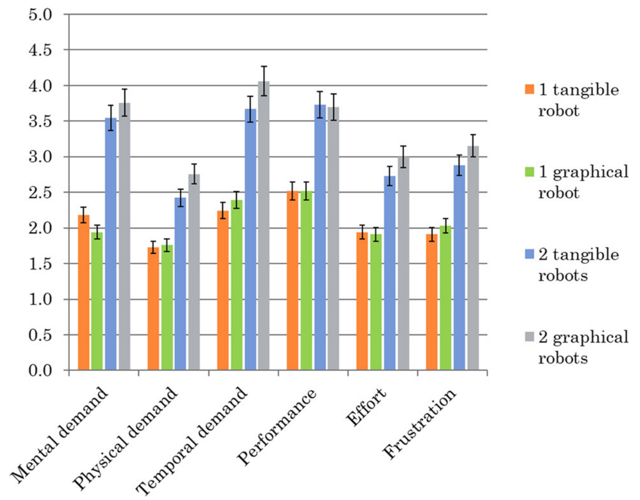

Fig. 17 NASA-TLX sub-scales means for one and two robots and in tangible and touch interaction technique

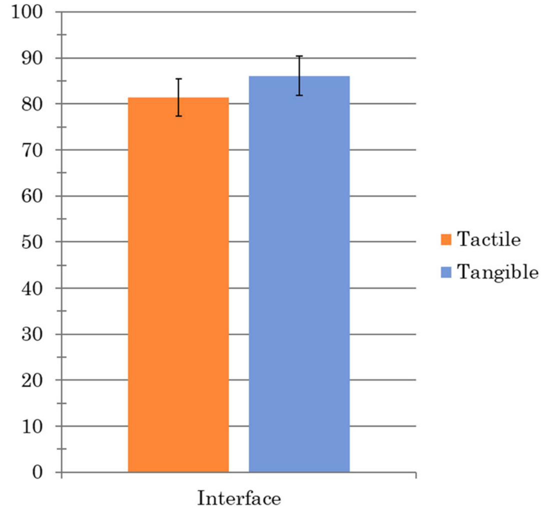

Fig. 18 SUS global scores means with error bars, for tangible and touch interaction technique

all in favor of tangibles except for the performance. Plus, the scores of all sub-scales are largely higher for tasks with two robots than the scores of tasks with one robot. However, if we notice the error bars we see that they overlap, which means that it is unlikely to find a statistically significant difference. Therefore, on each of the NASA-TLX sub-scales a paired (dependant) t-test has been conducted with the following alternate hypothesis: "participants' workload using the TUI is lower than when using the touch interface, with the same number of robots".

The t-test results show that, in a confidence interval of 95%, all p-values corresponding to all sub-scales are largely greater than 0.05. Nothing about comparing workloads in tangible and touch user interfaces, in this context of remotely controlling robots using a tabletop, can be concluded on based on these results. Unlikely to other results which are quite significant, we present them in the following subsections.

Another one-sided paired t-test, in a confidence interval of 95%, has been conducted on the data with the following alternate hypothesis: "participants' workload when performing with one robot is lower than when performing with two robots in the same interface". The results indicate that all *p-values* are less than 0.05, which means that performing with two robots is significantly more demanding than performing with one robot.

Our results of measuring usability show a significant difference of scores (calculated as a percentage) in favor of the tangible version, indicating that participants have experienced better usability in tangible than in touch interface. As shown in Fig. 18, the tangible interface had a higher mean score ($M = 86.02$, $SE = 2$) than the touch interface ($M = 81.17$, $SE = 2.39$), $t(31) = 1.99$, $p < 0.05$, $r = 0.34$. These results are obtained from a one-sided *paired t-test* in a 95% confidence interval, it is a one-sided t-test because we were expecting a difference between the scores of tangible and touch interface. As the Pearson's correlation coefficient (r) is between 0.3 and 0.5, we can say that the effect size is from medium to large. Although the error bars overlap, we can conclude that in this context of remotely controlling robots using a tabletop, the tangible interface has a better usability than the touch interface.

4.2 Post-experiment evaluations

At the end of the experiment, participants took a brief interview and discussion. The interview questions are shown in Appendix A.2. We asked our participants to evaluate the following statements on a Likert scale from 1 (strongly disagree) to 5 (strongly agree):

- Statement 1: The "robot" tangible object is easy to manipulate.
- Statement 2: The "robot" tangible object seems significant (meaningful) to you in relation to its role in the application.
- Statement 3: I had a full control on the "robot tangible object" while using it (not the robot).
- Statement 4: I had a full control on the "graphical robot object" while using it (not the robot).
- Statement 5: The tangible object "take picture" is easy to manipulate.
- Statement 6: The "take picture" tangible object seems significant (meaningful) to you in relation to its role in the application.

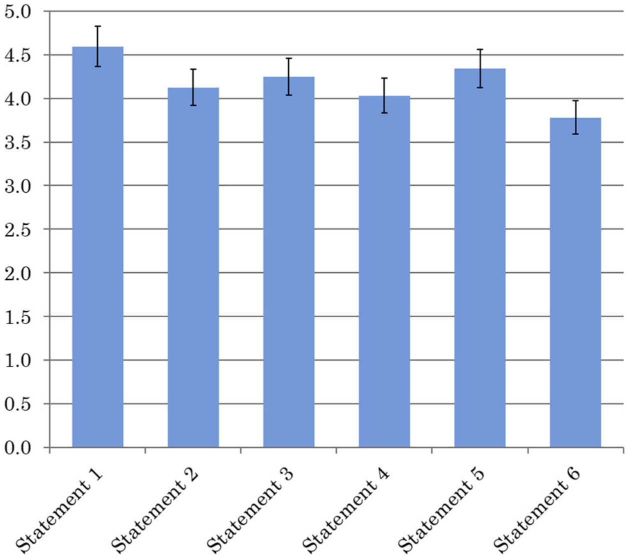

Fig. 19 Participants post experiment evaluations

Table 7 Post-experiment interview results

Statements	Mean	Standard error of the means	Standard deviation
Statement 1	4.59	0.15	0.84
Statement 2	4.13	0.18	1.01
Statement 3	4.25	0.17	0.95
Statement 4	4.03	0.18	1.06
Statement 5	4.34	0.14	0.79
Statement 6	3.78	0.21	1.18

Participants evaluations are illustrated in Fig. 19, it shows the means along with error bars. As we notice, participants were very satisfied with the usage of tangible objects, particularly since the standard deviations are relatively small. Table 7 describe this appreciation.

Some participants commented on the tangibles as *"very useful and straight forward, as they constitute the object and the whole process of interaction"*. For instance, they said *"when you place an object on the tabletop surface it detects it and triggers the final action, there is no need for intermediary actions, this can avoid us to choose among menu options"*. Furthermore, more than half of participants said that the experience with tangibles were more realistic and enjoyable compared to graphics (touch user interface); this is because of the haptic and the feeling of holding the object(s) in one's hand(s).

5 Discussion

The purpose of this study was to identify and understand how tangible interaction can be beneficial in a dual reality environment by interacting with one side (the virtual one) and in result changing the other side (the real one). It was the first study aiming to compare tangible and touch interaction techniques in a context of dual reality, and for remote robot control tasks, but only with a simplified task involving rectilinear movements, with stops, real robots and moving objects on an interactive tabletop. Our results show that the slight differences in users' workloads (in each sub-scale of the NASA-TLX), between touch and tangible interactions are statistically non-significant. However, they suggest that for tasks of control associated with low user workload it would be similar to use a touch or a tangible interface. The same applies for task completion time, task completion rate and overall relative efficiency as all of them show non-significant differences when using only one robot. Meanwhile, there is a significant difference between these two interaction techniques when using two robots, in favor of tangible interaction. The results may suggest that the more robots are in use, the higher the workload is, which needs further investigation. Therefore, reassessing the same task with more than two robots might enlarge the gap between tangible and touch interactions users' workloads, leading to more visible and noticeable differences.

Based on our findings, we can highlight the following recommendations: (1) in a workload demanding task of control, we recommend using tangible interaction instead of touch interaction, as it guarantees fewer errors comparing with touch interaction and a shorter task completion time, (2) in terms of engagement, we recommend tangible interaction over touch interaction as our participants were more engaged with tangible interaction, and they liked it more. Moreover, the SUS questionnaire outcomes indicate that tangible user interface has a better usability score than touch user interface, (3) in terms of rapidity and in this context of basically displacing objects between predefined locations, choose tangible interaction –with objects– on a tabletop's surface rather than touch interaction on a tabletop as this latter requires a longer time to complete tasks. This finding is in accordance with [37,39,119], (4) take into consideration the shape of physical objects and their color(s) in tangible user interface design, as our participants found it meaningful and expressive to use small-scaled colored objects reflecting the real side of dual reality objects. This outcome follows the results presented in [34,119].

Our findings also confirm Guo's work [49] in such way that even though users can remotely control the real robots using the mini-robots on the tabletop, they are unable to visualize the internal state of the real robots only from looking at the mini-robots. Therefore, internal state information of real robots is then –digitally– displayed on the tabletop's surface (information such as battery level, connection status, ...). Plus, our participants found that using tangibles reduces their focus and concentration, when using both hands at the same time (one hand for manipulating the robot and the other hand for taking pictures) and mainly when the two hands are spatially distant (e.g., right hand working on the right side of the tabletop and left hand working on the left side of the tabletop). This outcome is also in agreement with recommendations given in [34]. Furthermore, our participants found that using tangibles allowed them to count on their peripheral vision while grabbing objects, also particularly when using both hands distantly. This feature of tangible objects is due to their 3D nature according to our participants' feedback and remarks (see also [120]). This finding is also in agreement with recommendations given in [34]. Meanwhile, for the dual reality, some of our participants commented on its setup as "reflecting the reality as it is into a small scale" and "useful since it keeps the two environments symmetric, and if you are using the virtual part it gives you a global view on the real part". We believe that this second comment is because of the bird's eye view map of the intervention area shown on the tabletop. Furthermore, nine participants said that combining dual reality with tangibles gives a high impression of being in control of the other part and that it is realistic; this comment is supported by the results of the post-experiment evaluations shown in Sect. 4.2.

6 Conclusion and perspectives

We have presented in this work a study comparing users' performances on touch and tangible user interfaces, using an application dedicated to crisis management on a RFID-based tabletop interactive display. The application remotely controls robots using a tabletop in a dual reality setup. The application is implemented on tangible and touch user interfaces, and we relied on it to assess both tangible and touch interaction techniques. We have shown how tangible interaction outperforms touch interaction in effectiveness and efficiency for remote robots control as soon as users interact with more than one robot. Tangible interaction also performed better in usability, which is part of satisfaction assessment. As for workload, the study could not highlight any statistical difference between the two interaction techniques. In summary, this work shows that tangible interaction is better than touch interaction, in terms of rapidity, usability, effectiveness and efficiency, when interacting with both hands simultaneously.

However, applying our findings to other touch and tangible user interfaces has to be done with particular attention to the application context, further experimentation are needed before making strong conclusions about TUI versus touch user interfaces. One perspective of this work is to further investigate the users' workload with different configuration(s) of tasks (eventually their levels of complexity), and/or put more robots at once. In the near future, we plan to analyze more user data collected using *TobiiPro* eye tracker, that users were wearing during the experiment, and correlate it with our findings that we presented in this work. We also aim to do a similar experiment with multi-users, with more demanding and more stressful scenarios for stakeholders of crisis management and in other domains such as healthcare and education.

Acknowledgements We thank the automation department of the Laboratory of Industrial and Human Automation control, Mechanical engineering and Computer Science (LAMIH), particularly Marie-Pierre Pacaux-Lemoine and Patrick Millot for lending us the Lego robots (used in SUCRé project [6,121]). We also thank Lydia Habib for her help with the robots' programming and communication. The authors also thank warmly the anonymous reviewers for their numerous constructive remarks.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

A Appendix: mobile-robots study questionnaires

This study has other questionnaires than those presented in Sect. 3: pre-experiment questionnaire and post-experiment questionnaire.

A.1 Pre-experiment questionnaire

- Participant ID (given by experimenter): . . . .
- Age: . . . .
- Gender: ☐ Male ☐ Female
- Occupation and field: . . . .
- Dominant hand: ☐ Left ☐ Right

Circle your answers for each of the following questions.

- Have you ever used an interactive tabletop before?
  Very infrequently 1 2 3 4 5 very frequently
- Have you ever used a tangible interactive tabletop before?
  Very infrequently 1 2 3 4 5 very frequently
- How frequently do you use a touch-interface (smartphone, tablet ...)?
  Very infrequently 1 2 3 4 5 very frequently

- Have you ever used a big sized interface (such as a tabletop)?
  Very infrequently 1 2 3 4 5 very frequently
- Have you ever remotely controlled a robot?
  Very infrequently 1 2 3 4 5 very frequently

A.2 Post-experiment questionnaire

Questionnaire about the tangible objects and the tabletop general usage feedback: For each of the following statements, circle one answer that best describes your reactions to the objects.

- The "robot" tangible object is easy to manipulate.
  Strongly disagree 1 2 3 4 5 strongly agree
  Justification (optional):
- The "robot" tangible object seems significant (meaningful) to you in relation to its role in the application.
  Strongly disagree 1 2 3 4 5 strongly agree
  Justification (optional):
- I had a full control on the "robot tangible object" while using it (not the robot).
  Strongly disagree 1 2 3 4 5 strongly agree
  Justification (optional):
- I had a full control on the "graphical robot object" while using it (not the robot).
  Strongly disagree 1 2 3 4 5 strongly agree
  Justification (optional):
- The tangible object "take picture" is easy to manipulate.
  Strongly disagree 1 2 3 4 5 strongly agree
  Justification (optional):
- The "take picture" tangible object seems significant (meaningful) to you in relation to its role in the application.
  Strongly disagree 1 2 3 4 5 strongly agree
  Justification (optional):

Comments and suggestion about the experimentation (optional):

B Appendix: Tasks scenario and sequence

Fig. 20 Tasks and scenario progress. "T1" refers to task one, "T2" refers to task two, "S1" refers to system one (tangible version of the application) and "S2" refers to system two (touch version of the application)

References

1. Boden M, Bryson J, Caldwell D, Dautenhahn K, Edwards L, Kember S, Newman P, Parry V, Pegman G, Rodden T et al (2017) Principles of robotics: regulating robots in the real world. Connect Sci 29(2):124–129
2. Dunbabin M, Marques L (2012) Robots for environmental monitoring: Significant advancements and applications. IEEE Robot Autom Mag 19(1):24–39
3. Manti M, Cacucciolo V, Cianchetti M (2016) Stiffening in soft robotics: a review of the state of the art. IEEE Robot Autom Mag 23(3):93–106
4. Marconi L, Melchiorri C, Beetz M, Pangercic D, Siegwart R, Leutenegger S, Carloni R, Stramigioli S, Bruyninckx H, Doherty P et al (2012) The sherpa project: smart collaboration between humans and ground-aerial robots for improving rescuing activities in alpine environments. In: 2012 IEEE international symposium on safety, security, and rescue robotics (SSRR), pp. 1–4. IEEE
5. Chen JYC, Terrence PI (2008) Effects of tactile cueing on concurrent performance of military and robotics tasks in a simulated multitasking environment. Ergonomics 51(8):1137–1152
6. Habib L, Pacaux-Lemoine MP, Millot P (2016) Towards adaptability of levels of automation with Human-machine cooperation approach. In: 2016 IEEE international conference on systems, man, and cybernetics (SMC), pp 001081–001086, Budapest, Hungary. IEEE
7. Habib L, Pacaux-Lemoine MP, Millot P (2017) Adaptation of the level of automation according to the type of cooperative partner. In: IEEE international conference on systems, man, and cybernetics (SMC), 2017, pp 864–869. IEEE
8. Habib L, Pacaux-Lemoine MP, Millot P (2018) Human-robots team cooperation in crisis management mission. In: IEEE international conference on systems, man, and cybernetics. Miyazaki, Japan, pp 3209–3214
9. Lifton J, Paradiso JA (2009) Dual reality: merging the real and virtual. In: International conference on facets of virtual environments, pp 12–28. Springer
10. Lifton JH (2007) Dual reality: an emerging medium. PhD thesis, Massachusetts Institute of Technology
11. Merrad W, Habib L, Heloir A, Kolski C, Krüger A (2019) Tangible tabletops and dual reality for crisis management: case study with mobile robots and dynamic tangible objects. In: ANT, (2019) The 10th international conference on ambient systems. Networks and Technologies, Leuven, Belgium
12. LindenLab. Second life (2003). https://secondlife.com/
13. Rymaszewski Michael A, James W, Mark W, Catherine W, Cory O, Benjamin B-C (2007) Second life: the official guide. Wiley, Chichester
14. Back M, Kimber D, Rieffel E, Dunnigan A, Liew B, Gattepally S, Foote J, Shingu J, Vaughan J(2010) The virtual chocolate factory: mixed reality industrial collaboration and control. In: Proceedings of the 18th ACM international conference on multimedia, ACM, pp 1505–1506
15. Tcho Ventures, INC. Tcho Chocolate. https://tcho.com/. Accessed on 2019-05-02
16. Lifton J, Feldmeier M, Ono Y, Lewis C, Paradiso JA (2007) A platform for ubiquitous sensor deployment in occupational and domestic environments. In: Proceedings of the 6th international conference on information processing in sensor networks, pp 119–127. ACM
17. Lifton J, Mittal M, Lapinski M, Paradiso JA (2007) Tricorder: a mobile sensor network browser. In: Proceedings of the ACM CHI 2007 conference-mobile spatial interaction workshop
18. Raber F, Krüger A, Kahl G (2015) The comparison of performance, efficiency, and task solution strategies in real, virtual and dual reality environments. In: INTERACT 2015. Springer
19. Kahl G, Warwas S, Liedtke P, Spassova L, Brandherm B (2011) Management dashboard in a retail scenario. In: Workshop on location awareness in dual and mixed reality. International conference on intelligent user interfaces (IUI-11), pp 22–25
20. Spassova L, Schöning J, Kahl G, Krüger A (2009) Innovative retail laboratory. In: Roots for the future of ambient intelligence. European conference on ambient intelligence (AmI-09), 3rd, November, pp 18–21. Citeseer
21. Khan VJ, Nuijten KCM, Deslé N (2011) Pervasive application evaluation within virtual environments. In: 1st international conference on pervasive and embedded computing and communication system, pp 261–264
22. Merrad W, Heloir A, Kolski C (2017) Reformulating Clancey's generic tasks for bridging both sides of dual reality. In: 29ème conférence francophone sur l'Interaction Homme-Machine, pp 137–146. ACM
23. Arfib D, Filatriau JJ, Kessous L (2009) Prototyping musical experiments for tangisense, a tangible and traceable table. In: Proceedings of SMC 2009–6th sound and music computing conference 2009, Porto, Portugal, pp 247–252
24. Kubicki S, Lepreux S, Kolski C (2011) Evaluation of an interactive table with tangible objects: application with children in a classroom. In: Proceedings 2nd workshop on child computer interaction ”UI technologies and educational pedagogy, at CHI
25. Lebrun Y, Lepreux S, Haudegond S, Kolski C, Mandiau R (2014) Management of distributed RFID surfaces: a cooking assistant for ambient computing in kitchen. Procedia Comput Sci 32:21–28
26. Rekik Y, Grisoni L, Roussel N (2013) Towards many gestures to one command: a user study for tabletops. In: Paula K, Gary M, Gitte L, Janet W, Marco W (eds) Human-computer interaction – INTERACT 2013, pp 246–263, Springer, Berlin
27. Rekik Y, Vatavu RD, Grisoni L (2014) Match-up & conquer: a two-step technique for recognizing unconstrained bimanual and multi-finger touch input. In: Proceedings of the 2014 international working conference on advanced visual interfaces, AVI '14, pp 201–208, New York, NY, USA. ACM
28. Rekik Y, Vatavu RD, Grisoni L (2014) Understanding users' perceived difficulty of multi-touch gesture articulation. In: Proceedings of the 16th international conference on multimodal interaction, ICMI '14, pp 232–239, New York, NY, USA. ACM
29. Wobbrock JO, Morris MR, Wilson AD (2009) User-defined gestures for surface computing. In: Proceedings of the SIGCHI conference on human factors in computing systems, CHI '09, pp 1083–1092, New York, NY, USA. ACM
30. Goguey A, Nancel M, Casiez G, Vogel D (2016) The performance and preference of different fingers and chords for pointing, dragging, and object transformation. In: Proceedings of the 2016 CHI conference on human factors in computing systems, ACM, pp 4250–4261
31. Cattan E, Rochet-Capellan A, Bérard F (2016) Effect of touch latency on elementary vs. bimanual composite tasks. In: Proceedings of the 2016 ACM on interactive surfaces and spaces–ISS '16, Niagara Falls, Ontario, Canada, ACM Press, pp 103–108
32. Anthony L, Vatavu RD, Wobbrock JO (2013) Understanding the consistency of users' pen and finger stroke gesture articulation. In: Proceedings of graphics interface 2013, GI '13, Toronto, Ont., Canada, 2013. Canadian Information Processing Society, pp 87–94
33. Vatavu RD, Vogel D, Casiez G, Grisoni L (2011) Estimating the perceived difficulty of pen gestures. In: Campos P, Graham N, Jorge J, Nunes N, Palanque P, Winckler M (eds) Human-computer interaction - INTERACT 2011. Springer, Berlin, pp 89–106

34. Rekik Y, Merrad W, Kolski C(2019) Understanding the attention demand of touch and tangible interaction on a composite task. In: Proceedings of the 21st international conference on multimodal interaction, ICMI '19, New York, NY, USA. ACM. accepted
35. Mott ME, Vatavu RD, Kane SK, Wobbrock JO (2016) Smart touch: improving touch accuracy for people with motor impairments with template matching. In: Proceedings of the 2016 CHI conference on human factors in computing systems, CHI '16, pp 1934–1946, New York, NY, USA. ACM
36. Ungurean OC, Vatavu RD, Leiva LA, Plamondon R (2018) Gesture input for users with motor impairments on touchscreens: empirical results based on the kinematic theory. In: extended abstracts of the (2018) CHI conference on human factors in computing systems, CHI EA '18, pp LBW537:1-LBW537:6, New York. ACM, USA, NY
37. Tuddenham P, Kirk D, Izadi S (2010) Graspables revisited: multi-touch vs. tangible input for tabletop displays in acquisition and manipulation tasks. In: Proceedings of the SIGCHI conference on human factors in computing systems, pp 2223–2232. ACM
38. Don L, Smith SP (2010) Applying bimanual interaction principles to text input on multi-touch surfaces and tabletops. In: ACM international conference on interactive tabletops and surfaces - ITS '10, Saarbrücken, Germany. ACM Press, pp 253–254
39. Terrenghi L, Kirk D, Sellen A, Izadi S (2007) Affordances for manipulation of physical versus digital media on interactive surfaces. In: Proceedings of the SIGCHI conference on Human factors in computing systems, pp 1157–1166. ACM
40. Appert C, Zhai S (2009) Using strokes as command shortcuts: cognitive benefits and toolkit support. In: Proceedings of the SIGCHI conference on human factors in computing systems, CHI '09, New York, NY, USA, 2009. ACM, pp 2289–2298
41. Nacenta MA, Kamber Y, Qiang Y, Kristensson PO (2013) Memorability of pre-designed and user-defined gesture sets. In: Proceedings of the SIGCHI conference on human factors in computing systems, CHI '13, pp 1099–1108, New York, NY, USA. ACM
42. Nielsen M, Störring M, Moeslund TB, Granum E (2004) A procedure for developing intuitive and ergonomic gesture interfaces for hci. In: Antonio C, Gualtiero V (eds) Gesture-based communication in human-computer interaction, pp 409–420, Springer, Berlin
43. Morris MR, Wobbrock JO, Wilson AD (2010) Understanding users' preferences for surface gestures. In: Proceedings of graphics interface 2010, GI '10, pp 261–268, Toronto, ON, Canada, Canada. Canadian Information Processing Society
44. Kato J, Sakamoto D, Inami M, Igarashi T (2009) Multi-touch interface for controlling multiple mobile robots. In: CHI'09 extended abstracts on human factors in computing systems, pp 3443–3448. ACM
45. Hornecker E, Buur J (2006) Getting a grip on tangible interaction: a framework on physical space and social interaction. In: Proceedings of the SIGCHI conference on human factors in computing systems, CHI '06, New York, NY, USA. ACM, pp 437–446
46. Ishii H (2008) Tangible bits: beyond pixels. In: Proceedings of the 2nd international conference on Tangible and embedded interaction. ACM
47. Ullmer B, Ishii H (2000) Emerging frameworks for tangible user interfaces. IBM Syst J 39(34):915–931
48. Michael R, Alejandro C, Radhika N (2014) Programmable self-assembly in a thousand-robot swarm. Science 345(6198):795–799
49. Guo C, Sharlin E (2008) Utilizing physical objects and metaphors for human robot interaction. In: Proceedings of the artificial intelligence and the simulation of behaviour convention (AISB '08)
50. Guo C, Young JE, Sharlin E (2009) Touch and toys: new techniques for interaction with a remote group of robots. In: Proceedings of the SIGCHI conference on human factors in computing systems, pp 491–500. ACM
51. Krzywinski A, Mi H, Chen W, Sugimoto M (2009) Robotable: a tabletop framework for tangible interaction with robots in a mixed reality. In: Proceedings of the international conference on advances in computer enterntainment technology, ACM, pp 107–114
52. Jordà S, Geiger Günter AM, Kaltenbrunner M (2007) The reacTable: exploring the synergy between live music performance and tabletop tangible interfaces. In: Proceedings of the 1st international conference on Tangible and embedded interaction, pp 139–146. ACM
53. Anastasiou D, Ras E (2017) A questionnaire-based case study on feedback by a tangible interface. In: Proceedings of the 2017 ACM workshop on intelligent interfaces for ubiquitous and smart learning, pp 39–42. ACM
54. Kubicki S, Lepreux S, Kolski C (2012) RFID-driven situation awareness on TangiSense, a table interacting with tangible objects. Pers Ubiquit Comput 16(8):1079–1094
55. Schneider B, Jermann P, Zufferey G, Dillenbourg P (2011) Benefits of a tangible interface for collaborative learning and interaction. IEEE Trans Learn Technol 4(3):222–232
56. Tabard A, Hincapié-Ramos JD, Esbensen M, Bardram JE (2011) The elabbench: an interactive tabletop system for the biology laboratory. In: Proceedings of the ACM international conference on interactive tabletops and surfaces, pp 202–211. ACM
57. Detken K, Martinez C, Schrader A (2009) The search wall: tangible information searching for children in public libraries. In: Proceedings of the 3rd international conference on tangible and embedded interaction, pp 289–296. ACM
58. Buur J, Jensen MV, Djajadiningrat T (2004) Hands-only scenarios and video action walls: novel methods for tangible user interaction design. In: Proceedings of the 5th conference on designing interactive systems: processes, practices, methods, and techniques, ACM, pp 185–192
59. Mandryk RL, Scott SD, Inkpen KM (2002) Display factors influencing co-located collaboration. In: Conference supplement to ACM CSCW, p 2
60. Yvonne Rogers Y, Lindley S (2004) Collaborating around large interactive displays: which way is best to meet? Interact Comput 16(6):1133–1152
61. Scott SD, Grant KD, Mandryk RL (2003) System guidelines for co-located, collaborative work on a tabletop display. In: ECSCW 2003. Springer
62. Bouabid A, Lepreux S, Kolski C (2018) Study on generic tangible objects used to collaborate remotely on rfid tabletops. J Multimodal User Interfaces 12(3):161–180
63. Kubicki S, Lepreux S, Kolski C, Perrot C, Caelen J (2009) TangiSense: présentation d'une table interactive avec technologie RFID permettant la manipulation d'objets tangibles et traçables. In: Proceedings of the 21st international conference on association francophone d'Interaction Homme-Machine - IHM '09, Grenoble, France. ACM Press
64. Mediamatic. Symbolic table : 100% interface-free media player. https://www.mediamatic.net/en/page/15897/symbolic-table-100-interface-free-media-player. Accessed on 2019-08-21
65. Wall J (2009) Demo i microsoft surface and the single view platform. In: 2009 international symposium on collaborative technologies and systems, pp xxxi–xxxii. IEEE
66. Mazalek A, Reynolds M, Davenport G, Magerkurth C, Röcker C (2007) The tviews table for storytelling and gameplay. In: Concepts and technologies for pervasive games: a reader for pervasive gaming research, vol 1, pp 265–290. Shaker Verlag
67. Baudisch P, Becker T, Rudeck F (2010) Lumino: tangible blocks for tabletop computers based on glass fiber bundles. In: Proceedings of the 28th international conference on human factors in

computing systems–CHI ’10, pp 1165, Atlanta, Georgia, USA. ACM Press

68. Weiss M, Schwarz F, Jakubowski S, Borchers J (2010) Madgets: actuating widgets on interactive tabletops. In: Proceedings of the 23nd annual ACM symposium on user interface software and technology, pp 293–302. ACM
69. Hauert S, Reichmuth D (2006) Instant city, ein elektronischer musik bau spiel automat. http://www.hauert-reichmuth.ch/en/projekte/instant-city/, Accessed on 2019-08-21
70. Kubicki S (2011) Contribution à la prise en considération du contexte dans la conception de tables interactives sous l’angle de l’IHM, application à des contextes impliquant table interactive RFID et objets tangibles. PhD thesis, Université de Valenciennes et du Hainaut-Cambresis, France
71. Nakagaki K, Fitzgerald D, Ma ZJ, Vink L, Levine D, Ishii H (2019) inforce: Bi-directionalforce’shape display for haptic interaction. In: Proceedings of the thirteenth international conference on tangible, embedded, and embodied interaction, pp 615–623. ACM
72. Nakagaki K, Vink L, Counts J, Windham D, Leithinger D, Follmer S, Ishii H (2016) Materiable: rendering dynamic material properties in response to direct physical touch with shape changing interfaces. In: Proceedings of the 2016 CHI conference on human factors in computing systems–CHI ’16, pp 2764–2772, Santa Clara, California, USA. ACM Press
73. Colter A, Davivongsa P, Haddad DD, Moore H, Tice B, Ishii H (2016) SoundFORMS: manipulating sound through touch. In: Proceedings of the 2016 CHI conference extended abstracts on human factors in computing systems–CHI EA ’16, Santa Clara, California, USA, 2016. ACM Press, pp 2425–2430
74. Levine D, Shortridge W, Retzepi K, Alkestrup J, Ishii H (2018) Conjure. http://tangible.media.mit.edu/project/conjure/
75. Tang SK, Sekikawa Y, Leithinger D, Follmer S, Ishii H (2019) Tangible cityscape. http://tangible.media.mit.edu/project/tangible-cityscape/
76. Leithinger D, Follmer S, Olwal A, Ishii H (2014) Physical telepresence: shape capture and display for embodied, computer-mediated remote collaboration. In: Proceedings of the 27th annual ACM symposium on user interface software and technology, pp 461–470. ACM
77. Leithinger D, Follmer S, Olwal A, Ishii H (2015) Shape displays: spatial interaction with dynamic physical form. IEEE Comput Graphics Appl 35(5):5–11
78. Umapathi U, Shin P, Nakagaki K, Chin S, Xu T, Gu J, Walker W, Leithinger D, Ishii H (2018) Programmable droplets for interaction. https://tangible.media.mit.edu/project/programmable-droplets-for-interaction/
79. Umapathi U, Shin P, Nakagaki K, Leithinger D, Ishii H (2018) Programmable droplets for interaction. In: Extended abstracts of the 2018 CHI conference on human factors in computing systems - CHI ’18, pp 1–1, Montreal QC, Canada. ACM Press
80. Fleck S, Baraudon C, Frey J, Lainé T, Hachet M (2018) Teegi, he’s so cute: example of pedagogical potential testing of an interactive tangible interface for children at school. In: Proceedings of the 29th conference on l’Interaction Homme–machine - IHM ’17, ACM Press, Poitiers, France, pp 1–12
81. Frey J, Gervais R, Fleck S, Lotte S, Hachet M (2014) Teegi: tangible EEG interface. In: Proceedings of the 27th annual ACM symposium on User interface software and technology–UIST ’14, Honolulu, Hawaii, USA. ACM Press, pp 301–308
82. Frey J, Gervais R, Lainé T, Duluc M, Germain H, Fleck S, Lotte F, Hachet M (2017) Scientific outreach with Teegi, a tangible EEG interface to talk about neurotechnologies. In: Proceedings of the 2017 CHI conference extended abstracts on human factors in computing systems–CHI EA ’17, Denver, ACM Press, pp 405–408
83. Goc ML, Kim LH, Parsaei A, Fekete JD, Dragicevic JD, Follmer S (2016) Zooids: building blocks for swarm user interfaces. In: Proceedings of the 29th annual symposium on user interface software and technology, pp 97–109. ACM
84. Melcer EF, Isbister K (2018) Bots & (Main) frames: exploring the impact of tangible blocks and collaborative play in an educational programming game. In: Proceedings of the 2018 CHI conference on human factors in computing systems–CHI ’18, pp 1–14, Montreal QC, Canada. ACM Press
85. Nakagaki K, Follmer S, Dementyev A, Paradiso JA, Ishii H (2017) Designing line-based shape-changing interfaces. IEEE Pervasive Comput 16(4):36–46
86. Nakagaki K, Dementyev A, Follmer S, Paradiso JA, Ishii H (2016) ChainFORM: a linear integrated modular hardware system for shape changing interfaces. In: Proceedings of the 29th annual symposium on user interface software and technology - UIST ’16, pp 87–96, Tokyo, Japan, ACM Press
87. Villar N, Zhang H, Cletheroe D, Saul G, Holz C, Tim R, Oscar S, Misha S, Hui-Shyong Y, William F (2018) Project zanzibar: a portable and flexible tangible interaction platform. In: Proceedings of the 2018 CHI conference on human factors in computing systems–CHI ’18, pp 1–13, Montreal QC, Canada. ACM Press
88. Fitzmaurice GW, Ishii H, Buxton WAS (1995) Bricks: laying the foundations for graspable user interfaces. In: Proceedings of the SIGCHI conference on Human factors in computing systems, ACM Press, pp 442–449
89. Fitzmaurice GW, Buxton W (1997) An empirical evaluation of graspable user interfaces: towards specialized, space-multiplexed input. In: Proceedings of the ACM SIGCHI conference on human factors in computing systems, CHI ’97, ACM, New York, NY, USA, pp 43–50
90. Almukadi W, Stephane AL (2015) Blackblocks: tangible interactive system for children to learn 3-letter words and basic math. In: Proceedings of ITS, pp 421–424
91. Manches A, O’Malley C, Benford S (2009) Physical manipulation: evaluating the potential for tangible designs. In: Proceedings of the 3rd international conference on tangible and embedded interaction, pp 77–84. ACM
92. Marshall P (2007) Do tangible interfaces enhance learning? In: Proceedings of the 1st international conference on Tangible and embedded interaction, pp 163–170. ACM
93. Kubicki S, Wolff M, Lepreux S, Kolski C (2015) RFID interactive tabletop application with tangible objects: exploratory study to observe young children’ behaviors. Pers Ubiquit Comput 19(8):1259–1274
94. Everitt KM, Klemmer SR, Lee R, Landay JA (2003) Two worlds apart: bridging the gap between physical and virtual media for distributed design collaboration. In: Proceedings of the SIGCHI conference on human factors in computing systems, ACM, pp 553–560
95. Ullmer B, Ishii H (1997) The metadesk: models and prototypes for tangible user interfaces. In: Proceedings of symposium on user interface software and technology (UIST 97), ACM
96. Price S, Rogers Y, Scaife M, Stanton D, Neale H (2003) Using tangibles to promote novel forms of playful learning. Interact Comput 15(2):169–185
97. Pangaro G, Maynes-Aminzade D, Ishii H (2002) The actuated workbench: computer-controlled actuation in tabletop tangible interfaces. In: Proceedings of the 15th annual ACM symposium on User interface software and technology, pp 181–190. ACM
98. Richter J, Thomas BH, Sugimoto M, Inami M (2007) Remote active tangible interactions. In: Proceedings of the 1st international conference on Tangible and embedded interaction, pp 39–42. ACM
99. Riedenklau E, Hermann T, Ritter H (2012) An integrated multimodal actuated tangible user interface for distributed collaborative

planning. In: Proceedings of the sixth international conference on tangible, embedded and embodied interaction, pp 169–174. ACM

100. Ducasse J, Macé M, Oriola B, Jouffrais C (2018) Botmap: non-visual panning and zooming with an actuated tabletop tangible interface. ACM Trans Comput Hum Interact 25(4):24:1–24:42
101. McGookin D, Robertson E, Brewster S (2010) Clutching at straws: using tangible interaction to provide non-visual access to graphs. In: Proceedings of the SIGCHI conference on human factors in computing systems, pp 1715–1724. ACM
102. Lucchi A, Jermann P, Zufferey G, Dillenbourg P (2010) An empirical evaluation of touch and tangible interfaces for tabletop displays. In: Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction, pp 177–184. ACM
103. North C, Dwyer T Lee Bongshin, Fisher Danyel, Isenberg Petra, Robertson George, Inkpen Kori (2009) Understanding multi-touch manipulation for surface computing. In: *IFIP Conference on Human-Computer Interaction*, pages 236–249. Springer
104. Ayoung H, Gun LD, Bülthoff Heinrich H, Il SH (2017) Multimodal feedback for teleoperation of multiple mobile robots in an outdoor environment. J Multimodal User Interfaces 11(1):67–80
105. Abich J, Barber DJ (2017) The impact of human-robot multimodal communication on mental workload, usability preference, and expectations of robot behavior. J Multimodal User Interfaces 11(2):211–225
106. Biswas M, Romeo M, Cangelosi A, Jones RB (2020) Are older people any different from younger people in the way they want to interact with robots? scenario based survey. J Multimodal User Interfaces 14(1):61–72
107. ITU-T. The Tactile Internet ITU-T Technology Watch Report, 2014
108. Kubicki S, Lepreux S, Lebrun Y, Dos Santos P, Kolski C, Caelen J (2009) New human-computer interactions using tangible objects: Application on a digital tabletop with RFID technology. In: International conference on human-computer interaction, Springer, pp 446–455
109. Nowacka D, Ladha K, Hammerla NY, Jackson D, Ladha C, Rukzio E, Olivier P (2013) Touchbugs: actuated tangibles on multi-touch tables. In: Proceedings of the SIGCHI conference on human factors in computing systems, pp 759–762
110. Christensen Dusty. 30 years after the chernobyl meltdown, why is the ukrainian government pushing nuclear energy? https://www.thenation.com/article/30-years-after-the-chernobyl-meltdown-why-is-the-ukrainian-government-pushing-nuclear-energy/. Accessed on 2019-08-04
111. Sylvain Pedneault. Fire inside an abandoned convent in massueville, quebec, canada. https://en.wikipedia.org/wiki/Structure_fire#/media/File:Fire_inside_an_abandoned_convent_in_Massueville,_Quebec,_Canada.jpg. Accessed on 2019-08-04
112. CNN. The battle of aleppo in 20 photos. https://edition.cnn.com/2016/12/22/middleeast/syrian-regime-takes-full-control-of-aleppo/index.html, 2014. Accessed on 2019-09-19
113. Marzat J, Piet-Lahanier H, Kahn A (2014) Cooperative guidance of lego mindstorms nxt mobile robots. In: 2014 11th international conference on informatics in control, automation and robotics (ICINCO), vol 2, pp 605–610. IEEE
114. Hart SG (1986) NASA task load index (TLX). Vol 1.0; Paper and pencil package
115. Brooke J (1996) Sus-a quick and dirty usability scale. In: Usability evaluation in industry. Taylor and Francis, London, pp 189–194
116. IEC. ISO/IEC TR 9126-4:2004 - Software engineering – Product quality – Part 4: Quality in use metrics. https://www.iso.org/standard/39752.html. Accessed on 2019-08-04
117. Justin Mifsud. Usability Metrics – A Guide To Quantify The Usability Of Any System. https://usabilitygeek.com/usability-metrics-a-guide-to-quantify-system-usability/. Accessed on 2019-08-05
118. Assila A, Ezzedine H, deOliveiraKathia M (2016) Standardized usability questionnaires: Features and quality focus. Electron J Comput Sci Inf Technol eJCIST 6(1):15–31
119. Hornecker E (2006) Physicality in tangible interaction: bodies and the world. First Steps Phys, p 21
120. Saskia B, van den Hoven E, Eggen B (2010) Design for the periphery. EuroHaptics 2010:71
121. Pacaux-Lemoine MP, Millot P (2016) Adaptive Level of Automation for risk management. IFAC-PapersOnLine 49(19):48–53