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Product interface design: A participatory approach based on virtual reality

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Abstract

The usability of the user interface is a key aspect for the success of several industrial products. This assumption has led to the introduction of numerous design methodologies addressed to evaluate the user-friendliness of industrial products. Most of these methodologies follow the participatory design approach to involve the user in the design process. Virtual Reality is a valid tool to support Participatory Design, because it facilitates the collaboration among designers and users.

The present study aims to evaluate the feasibility and the efficacy of an innovative Participatory Design approach where Virtual Reality plays a 'double role': a tool to evaluate the usability of the virtual product interface, and a communication channel that allows users to be directly involved in the design process as co-designers.

In order to achieve these goals, we conducted three experiments: the purpose of the first experiment is to determine the influence of the virtual interface on the usability evaluation by comparing "user–real product" interaction and "user–virtual product" interaction. Subsequently, we tested the effectiveness of our approach with two experiments involving users (directly or through their participation in a focus group) in the redesign of a product user interface. The experiments were conducted with two typologies of consumer appliances: a microwave oven and a washing machine.

Keywords: Participatory design; Virtual reality; Usability; Product interface design

1. Introduction

The design of the interface is a critical task in the product development process, because it directly influences the customers' satisfaction and, consequently, the success of the product on the market. One of the most important characteristic of a user interface is usability: as stated by the ISO 9241 norm part 11 (ISO/DIS 9241-11), usability is "the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use".

Recent research (Muller and Kuhn, 1993; Schuler and Namioka, 1993; Reich et al., 1996; Finn and Blomberg, 1998; Demirbileka and Demirkan, 2004) has described the Participatory Design (PD) as an emerging approach that considers users as the core of design processes and aims to guarantee usability, simplicity and intelligibility of the product. The peculiarity of such a method is due to the direct involvement of end users during all phases of the product development; the user actively takes part in the whole project procedure, and his contribution has a fundamental significance in the product characterisation because he/she drives the assessment of any design variables.

The effectiveness of the PD approach in the product design is well documented in literature (Schuler and Namioka, 1993; Finn and Blomberg, 1998; Kujala, 2003), but there are also apparent limits of the current approaches that we have tried to tackle through the introduction of specific technologies and tools:

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- The designers' proposals have to be presented as expensive prototypes, because many users cannot understand theoretical concepts and prefer discussing existing products or realistic mock-ups (Kima et al., 2004; Nevalaa and Tamminen-Peter, 2004; Olsson and Jansson, 2005; Sharma et al., 2008). A physical mock-up of the product concept can be realised only in the final stages of the development process, causing a delay in discovering design problems.
- The designers and the users do not share a common language and have different cultural backgrounds, thus complicating communication and cooperation in the design activities. Generally, designers collect suggestions and ideas from the users through questionnaires and interviews (http://www.usabilitynet.org/trump/methods/methodslist.htm) but these methods are inadequate to implement a real PD approach (Carmel, 1993; Bruseberga and McDonagh-Philp, 2002; Isomursua et al., 2004; Dinka and Lundberg, 2006; Luck, 2007).

In other words PD suffers from a lack of tools that are able to quickly transmit the designers' intent to the users giving back suggestions, ideas, and a performance evaluation. In our opinion, Virtual Reality (VR) may be used to develop specific tools that are able to solve these problems because in a Virtual Environment (VE) it is possible to design, simulate, analyse and test the digital product in a very user-friendly way. Thanks to its peculiar characteristics (real time interaction, more intuitive input devices and stereoscopic visualisation), VR appears to be a highly appropriate medium for the involvement of users during the design activities. We consider VR systems the tools that, more than others, have the right requirements for a PD approach because:

1. Virtual Prototypes may replace the physical mock-ups with a notable reduction of costs and ''time-to-market''.
2. Virtual Reality may be considered as a ''*communication channel*'' (Reich et al., 1996) among designers and users. Thanks to VR, communication becomes a continuous process of perspective, conceptualisation, and information exchange, always requiring interpretation and translation of both the designers and users who are learning, building and evolving shared meanings of design situations.

The use of VR in PD has been tested in several application fields like road planning, medicine, and work place layout (Davis, 2004; Dinka and Lundberg, 2006; Finn and Blomberg, 1998; Heldal, 2007; Mobach, 2008; Mogensen and Shapiro, 1998; Reich et al., 1996; Schuler and Namioka, 1993) but it has scarcely been tested for industrial product design and, in particular, there are no studies on usability tests of the product interface in VE.

In order to verify these considerations, we have developed a system named VP4PaD (Virtual Prototyping for Participatory Design) (Bruno et al., 2006, 2007) that aims to favour the user/designer collaboration, through the direct interaction with a 3D model of the product interface; this system helps to overcome the existing limits of PD approaches which use drawings, notes or interviews. VP4PaD allow the users to sketch the product interface selecting the functional elements (Human Interface Elements (HIEs) (Han et al., 2002)), such as buttons, handles, switches, etc.) that they prefer, and to place them in the desired layout. With this tool the user creates a virtual prototype that is fully operational in order to reproduce (in the VE) the behaviour of the product interface. These virtual prototypes are employed to rapidly perform the usability test reducing time and costs of the evaluation and having the possibility to involve end users of a product from the earliest stages of the design process without the need of a physical mock-up and with the advantage of being able to assess several design options in VE.

The main contribution of this paper is to determine the effectiveness of VP4PaD for the involvement of final users in usability analyses and PD sessions. This evaluation has been done through three studies that analyse three different issues:

1. The main issue is that VE may invalidate the usability tests done with the virtual product. In fact, it is apparent that the interaction with a virtual product is not as easy as the interaction with a real product, because the VR devices may create an additional difficulty for the user that have to complete the test. To give an answer to this question we have conducted a study, reported in Section 4, that compares the ''user–real product'' interaction and ''user–virtual product'' interaction, in order to determine the influence of the virtual interface on the usability evaluation done through a digital mock-up.
2. Since the direct use of VR tools may not be acceptable by the end users, we try to adapt VP4PaD to conduct focus groups analyses where an operator interacts with the virtual prototype, while the end users are asked to give a feedback about the product interface. A second study, reported in Section 5, evaluates the efficacy of this approach comparing the usability of the interface of a commercial microwave oven with a new one redesigned by taking into account the data collected from a focus group analysis done with VP4PaD.
3. Finally, we have evaluated how VP4PaD may support the direct involvement of the end users as co-designers, giving them the possibility to sketch the product interface and immediately test its functionalities. The study, reported in Section 6, evaluates if this approach may improve the product interface and may facilitate the involvement of end users in the initial design phases.

The usability tests, realised in these three studies, refer to the ISO 9241 norm, part 11, that defines the elements which have to be detected through empirical usability tests: efficiency (time required to carry out a task), effectiveness (number of mistakes made and their importance) and satisfactory use of a product.

2. Related work

2.1. Product interface usability

User Interface Design is generally associated with software interfaces and is frequently referred to as a human–computer interface. However, User Interface Design takes place whenever users interact with products (a simple watch, a DVD player, an aircraft cockpit, etc.). Product interface design is strictly associated with product usability, acceptance, and marketability.

Woodson et al. (1992) demonstrate that the application of the traditional concept of usability to the consumer electronic products is not successful. They consider the interface attractiveness as one of the most important criteria for the design of consumer products together with safety, operability, and maintainability.

In another study (Han et al., 2002), the authors intend to help the usability practitioners in consumer electronics industry in various ways. The research supports the evaluators' plan and conducts usability evaluation sessions in a systematic and structured manner.

Han et al. (2000, 2001) provide a new definition of usability, applicable to consumer electronic products. They define usability as the users' degree of satisfaction with the product in respect to both performance and image.

The research described in Kima et al. (2004) explores different ways to use some "body-based interfaces" for interacting with wearable computers. The authors describe a usability test conducted to compare the performance and subjective preference of the four different styles of the interfaces.

In Isomursua et al. (2004), the authors describe a method for involving young girls in a concept design process of a portable CD player. The authors have adopted a web-based storytelling environment where the target group is encouraged to create usage scenarios of a mobile terminal that would support their activities in a virtual community. With this method, the authors have received lots of valuable input from the girls that have been involved in functional and industrial design of the product concept.

The approach proposed in Kuutti et al. (2001) uses the Web to assess the usability of an industrial product through virtual prototypes. The research is founded on the idea that it is not possible to relegate the relationship between man and artefact to a psycho-individual frame. The knowledge of social and contextual aspects is also necessary to fully exploit systems and interfaces. The internationalisation of markets underlines the need to assess and examine products during the design phase, with users from different cultures, and in worldwide environments. The software developed by the authors has been designed to carry out usability tests at a distance. The most significant and useful result of the experiments was that virtual prototypes can be indeed used in recognising usability problems, like problems in the logic of functioning, confusing positions of input/output (I/O) devices, etc.

2.2. Virtual reality and PD

In Reich et al. (1993), the authors describe an exhaustive bibliography on computer tools and techniques to support participation activities. In Mogensen and Shapiro (1998), a review of experiments and prototypes of different IT applications (participatory planning GIS, 3D models and communication platforms).

Among all Computer-aided PD tools and techniques, VR has roused a lot of interest because its techniques can better support the collaboration between users and designers. In Ehn et al. (1996), Davies et al. (2001), and Davis (2004), the authors describe a software (*Envisionment*) that is able to support and facilitate participatory design in work places through VR. Thanks to this software, users may plan a work place that reflects their needs. After that, they may also assess the results of their choices by analysing the virtual prototype from several points of view, by surfing within the virtual work place, choosing between several settings (lights, textures).

In Heldal (2007), the author provides a more detailed description of the use of VR models that support involvement and collaboration in the road planning process. They have observed that the effects of changes by using different views and accurate details of the 3D model have been very helpful in the research of "optimal" solution. Mobach (2008) determines the effects of a PD approach supported by VR for the realisation of two community pharmacies. The paper assesses whether VR made participants change a particular design and to what extent this affects staff satisfaction and construction costs.

In Wallergard et al. (2008), the authors present a suggested methodology based on VR technology, which enables people with cognitive disabilities to communicate their knowledge and experiences of public transport systems. Users interacted with the VR system by verbally describing their actions to the person controlling the VR system and/or pointing with a laser pointer while seated in front of three screens on which the VE was projected.

In Jin et al. (2001), the authors introduce a Tele-immersive Collaborative Virtual Environment System in which an anchor in Virtual Studio interacts with a participant in CAVE for collaborative work. The paper presents an overview of the GAMSUNG Engineering project developed with HYUNDAI Motor Company. The overall goal of the project is to develop measuring and analysing methodology for human emotion objectively and product application technology that is appealing to human emotion.

3. Experimental set-up

VP4PaD has been developed for product interface design and it is a tool which requires a specific implementation in relation to the product that has to be analysed. In our research, we implemented two particular product interfaces to test our approach: a washing machine and a microwave oven.

VP4PaD may be used as follows: the user may interact with the product through the mediation of an operator or by himself. The first procedure ensures the definition and the use of the product interface if the user is not familiar with hardware and/or software; whereas the second procedure, more frequently carried out when users have good computer skills, allows a more direct involvement of the user despite the increasing cognitive load (due to the use of virtual devices) which is necessary to reach the final objective.

3.1. Hardware devices

The set-up we used to test our approach (Fig. 1), allows a visualisation in passive stereoscopy and it is made of:

- a $1.8 \times 1.2\ m^2$ retro-projected screen;
- two DLP NEC video-projectors with 1024×768 resolution and a brightness of 3000ANSI/lumen;
- a computer with a Centrino 2Duo processor (2.13 GHz, 2 GB of RAM and *Nvidia Quadro FX-3500* video card with two outputs);
- glasses with circular polarisation filters able to guarantee freer movements, thus maintaining the stereoscopic effect. The transmission of the filters is equal to 38%;
- a support for the two projectors and a mirror to reduce the distance of the projection.

The devices used for the user/product interaction are:

- a *5th Dimension Technologies Data Glove* with 15 sensors through which the user may activate various control panels;
- a 3D joystick, realised by modifying a commercial joystick, through which the user may control both the selection of objects and the three video cameras managing the points-of-view (Fig. 2).

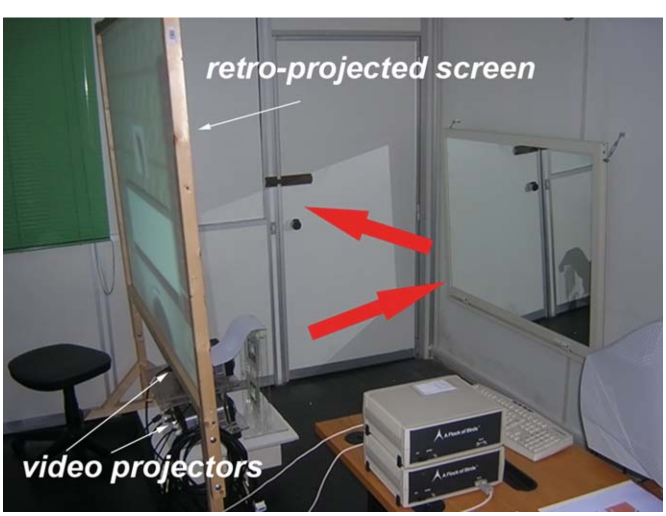

Fig. 1. Set-up used for the projection.

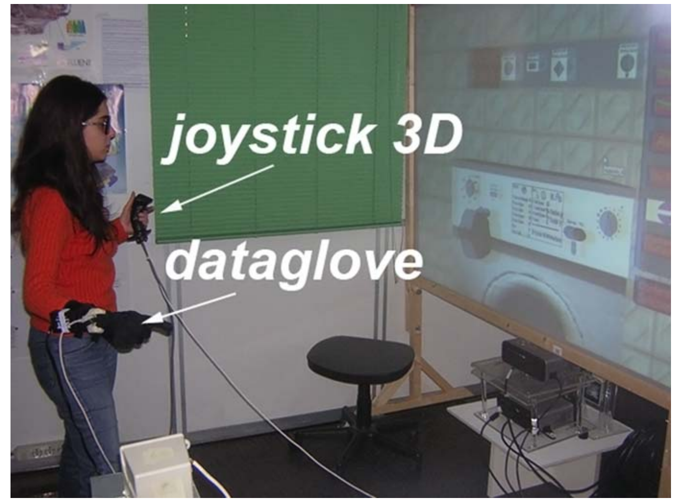

Fig. 2. Interaction devices.

- a tracking device (*Ascension Flock of Bird*) with two sensors: one connected to the glove to determine position and orientation of the user's right hand and another one may be used for head tracking, or placed inside the 3D joystick to improve navigation tools.

3.2. The virtual environment

Our efforts to achieve a more natural and comfortable interaction for the user are particularly important especially if the target is represented by end users who have limited computer skills. One must, therefore, try hard to avoid the user's uneasiness whilst facing such tools. For this reason we focused carefully on the environment. In PD, the use of an immersive (or semi-immersive) environment allows to improve the user's perception of the prototype, compared to traditional visualisation on a monitor, on condition that the visualisation is qualitatively satisfying in terms of immersivity and rendering. The use of a large display, like the projection system described in the previous section, allows us to visualise the virtual prototype in real scale, which is important in order to evaluate the understandability of interface items, icons or texts used to explain the meaning of the interface items.

The real scale visualisation has been obtained measuring the size of the object projected on the screen and comparing it with the size of the real object.

The stereoscopic visualisation has been done setting an interpupillary distance of 70 mm, a value that is usually comfortable for most people.

During the tests the head tracking has not been used in order to avoid any possible problem related to the latency or the jitter of the sensors.

The VE has been created using *Virtools Dev 4.0* which allows developers to rapidly create interactive 3D applications. Most of the implementation work has regarded the simulation of the product interface behaviour employed in virtual usability tests. The logic of the product interface has been replicated within the code of the VR application using an object-oriented approach, which allows us to quickly create different prototypes changing the types and the properties of the items (button, knob, display, etc.), employed to create the product interfaces.

3.3. Simulation of the interaction through the virtual prototype

In order to generate the sensation of an immersion into a VE, it is necessary to simulate all the perceptive stimuli coming from the real world. At present, it is still particularly difficult to simulate tactile stimuli and reactions coming from real objects: simulations based on visual stimuli are instead particularly effective (sight has the privilege of being the sense *par excellence*). The user easily learns how to code a visual stimulus as the effect of an action, thus becoming aware of such correspondence that he/she will be able to reproduce in the future. The user's training phase, carried out before the interaction with the virtual prototype, notably improves the user's familiarity with the virtual interface.

During the adjustment of the system, we particularly focused on the design of a product/user interaction as similar as possible to the real one. A large number of tests were carried out, in order to simulate tactile feedback (not implemented in the particular set-up used); the experimental evolution led to a perceptive solution (sufficiently immediate in terms of cognition) of the hand–virtual interface collision obtainable through both a visual and auditory feedback.

Visual feedback concerns the variation of colour (red indicates the collision with the virtual object; whereas green shows that a certain task has been carried out) or the variation of the position of the currently used interface element. As soon as the user draws his/her hand away from the interface, the selected element returns to its original colour and position (Fig. 3). Auditory feedback, on the other hand, is a ''beep'' sound that the user hears when he/she gives instructions (at the same time the selected button becomes green). The interface gives further responses through the display and/or LEDs which are able to send feedback to the user on the activation of a certain function.

In order to increase the perception of tactile feedback, we made sure that the virtual hand reacted to the collision with the interface of the prototype. The solution we adopted ensures that the hand changes colour in contact with the interface; so the virtual hand becomes red when it reaches the surface of the object and more and more transparent as it crosses the collision plane (Fig. 3).

4. Study 1: validation of the usability test in VR

4.1. Experimental task and participants

The first study has been designed in order to verify whether VR can be a valid tool to test the usability of the product interface. In other words, the experiment had to verify if we may define a test in VR as an alternative to traditional methods for usability evaluation of industrial products, and if the interaction with the virtual interface does not invalidate the usability evaluation itself. We want to establish whether and to what extent the Virtual Reality devices may distort the usability assessment of the real product (Bruno et al., 2005).

In this experiment, we compare the results between ''user–real product'' interaction and ''user–virtual product'' interaction, in order to determine the influence of the virtual interface on the usability evaluation.

The experiment illustrated in this section refers to the assessment of the usability of a product, currently present on the market (a microwave and electrical oven) thanks to usability tests based on two different approaches: the first focusing on the interaction between end users and the real

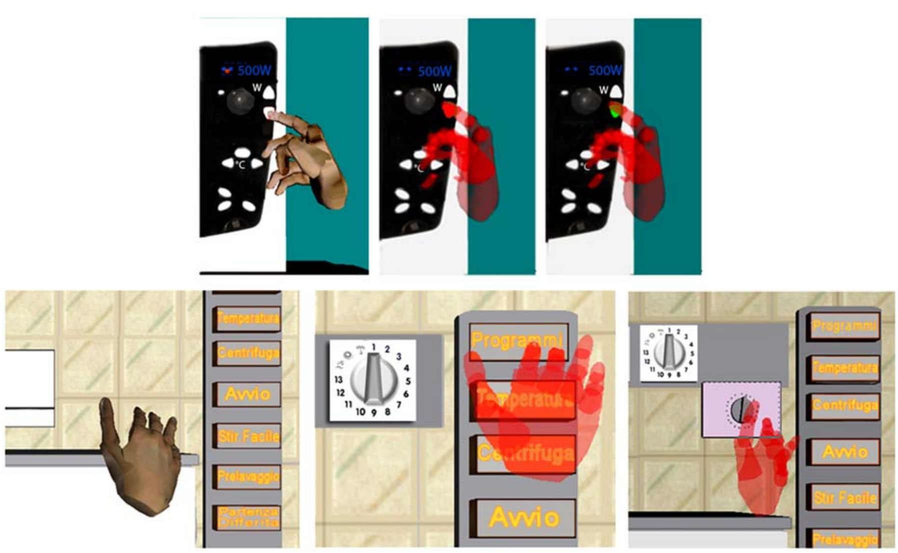

Fig. 3. Response of the interface and the hand during the interaction with the virtual prototype.

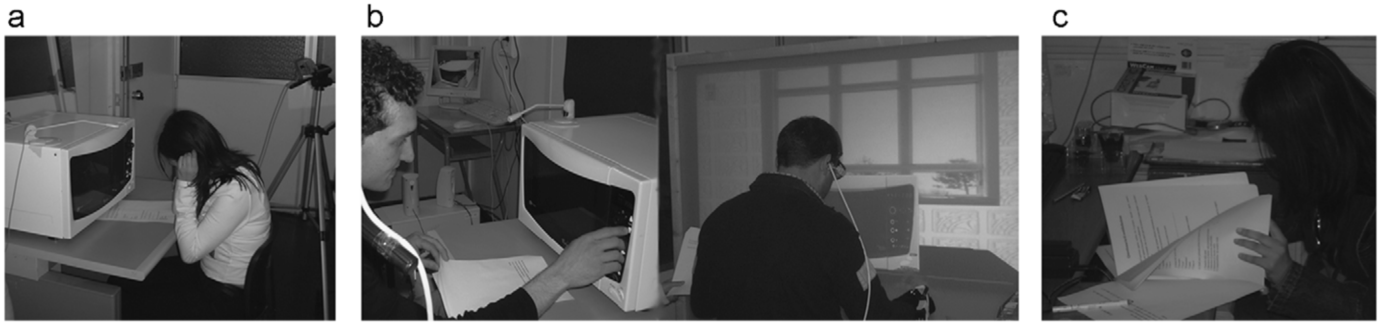

Fig. 4. Operative phase of the test: (a) filling in questionnaires, (b) trying out the product (real and virtual), and (c) filling in of the satisfaction questionnaire.

product and the other focusing on the interaction between users and a model of the oven within a VE.

In order to carry out the test (which took place in the Department of Mechanical Engineering, University of Calabria) we chose 2 samples of 10 mechanical engineering students aged 23–26 (9 males and 11 females). Both samples of users A ($A_1, \ldots, A_{10}$) and B ($B_1, \ldots, B_{10}$) presented homogeneous features especially in concern to the knowledge of the product we were testing (only 5 students per group owned and could use a microwave oven).

Sample A were asked to carry out the usability test with the real interface, whereas sample B were asked to assess the usability of the virtual interface.

4.2. Experimental design and procedure

The usability testing was carried out by observing a first group of users during their interaction with a real object and observing a second group of users during their interaction with the corresponding virtual model.

In concern to the object to be tested, we would like to point out that, since the testing had to focus on a comparison between data obtained through the user's interaction with a real object and data obtained through the user's interaction with the object in a VE, we decided to choose a common electrical appliance—a recently produced microwave oven—which included also in its VR reproduction several functions. This allowed users to carry out several tasks of varied difficulty.

The experiment was carried out mainly in three phases:

- an analytical phase during which we organised the entire carrying out of the test. We defined the procedures to be used during the test, the assessment tools (user-profile questionnaire, user–object interaction phase, satisfaction questionnaire, virtual interface assessment questionnaire), the two kinds of users' tasks and choice criteria;
- an operational phase during which the sample of users, after having been told about the aim of the research, carried out the test with either the real product or the virtual product;
- an assessment phase during which we analysed all the information we collected, thanks to questionnaires and the observation of users during the test.

During the operational phase each single user carried out three activities (Fig. 4):

(1) filling in the user-profile questionnaire;
(2) the actual testing of the (real or virtual) object, carrying out assigned tasks;
(3) filling in a questionnaire on the degree of satisfaction.

Furthermore, only the sample of users who carried out the test in a VE was trained, in order to be able to interact with the virtual system (learning how to adapt to stereoscopic visualisation and how to use the glove as an input device). At the end of the test the users also filled in a questionnaire concerning their approach with the virtual interface (difficulties in using interactive environment, perceptive level of the simulated reality, etc.)

The questionnaire identifying the user's profile, made up of 12 questions and aiming to deepen our knowledge of the single user, allowed us to obtain information on his/her level of technological knowledge (knowledge and familiarity of computer tools) and on his/her experience in using the product used during the test (knowledge and use of electrical and microwave ovens).

During the actual interaction with the product test, we asked the user, who was facing the object (real or virtual) to carry out four tasks presented as realistic scenarios (in order to make the user feel involved) and which gradually became more difficult to carry out. We told the user about one task at a time in order to favour his/her concentration and avoid misunderstandings.

During the test, we carefully observed the users and timed them, in order to take note of the amount of time needed to fulfil the task; we also wrote down any aspect, which could be useful for the usability evaluation (mistakes, comments, calls for help, expressions, etc.) (Fig. 5a). Furthermore, the use of a video camera allowed us to re-examine each single test carefully (Fig. 5b). The tests realised in VR were recorded by placing a polarising filter in front of the camera.

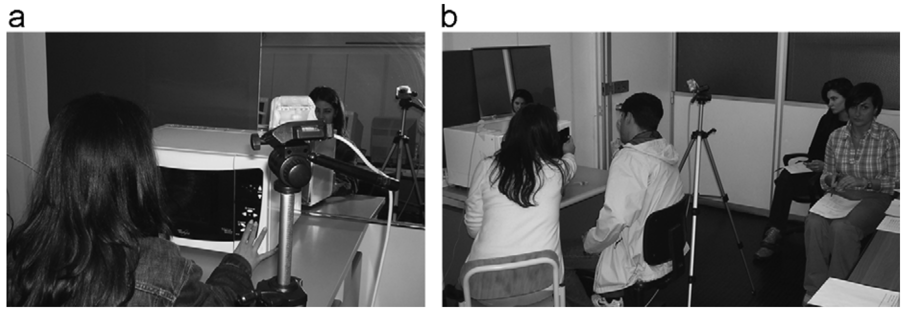

Fig. 5. Set up used during usability tests with real product.

Table 1
One-way ANOVA tables for number of errors.

		Sum of squares	Df	Mean square	F	Sig.
Task 1	Between groups	0.167	1	0.167	1.00	**0.37**
	Within groups	0.667	4	0.167		
	Total	0.833	5			
Task 2	Between groups	0.050	1	0.050	0.20	**0.66**
	Within groups	4.500	18	0.250		
	Total	4.550	19			
Task 3	Between groups	0.173	1	0.173	2.54	**0.14**
	Within groups	0.750	11	0.068		
	Total	0.923	12			
Task 4	Between groups	0.200	1	0.200	0.54	**0.47**
	Within groups	6.600	18	0.367		
	Total	6.800	19			

		N	Mean	Std. dev.	Std. error	Lower bound	Upper bound	Min	Max
Task 1	Sample A	3	1.33	0.577	0.333	−0.10	2.77	1	2
	Sample B	3	1.00	0.000	0.000	1.00	1.00	1	1
	Total	6	1.17	0.408	0.167	0.74	1.60	1	2
Task 2	Sample A	10	1.40	0.516	0.163	1.03	1.77	1	2
	Sample B	10	1.30	0.483	0.153	0.95	1.65	1	2
	Total	20	1.35	0.489	0.109	1.12	1.58	1	2
Task 3	Sample A	9	1.00	0.000	0.000	1.00	1.00	1	1
	Sample B	4	1.25	0.500	0.250	0.45	2.05	1	2
	Total	13	1.08	0.277	0.077	0.91	1.24	1	2
Task 4	Sample A	10	1.70	0.483	0.153	1.35	2.05	1	2
	Sample B	10	1.50	0.707	0.224	0.99	2.01	1	3
	Total	20	1.60	0.598	0.134	1.32	1.88	1	3

At the end of the interaction with the product, we asked the users to fill in a satisfaction questionnaire, made up of 11 questions, and the collected data allowed us to evaluate the users' overall degree of satisfaction and their well-being or sense of unease perceived after having used the product, as well as problems related to specific aspects of the product itself (content, structure, graphic interface).

4.3. Results

As we have already pointed out, the main purpose of the present experiment is an assessment of the reliability of a usability test in a VE, with a user interacting with the product interface through VR. Thus, the first step one must make is that of establishing whether and to what extent VR devices may distort the usability assessment of the real product. Therefore, the analysis of the goals achieved thanks to the test focused on the most significant data regarding the virtual interface assessment, deliberately neglecting the usability assessment of the specific product used during the test. The analysis of variances (ANOVA) were used to analyse the number of errors, the degree of satisfaction and the task completion times.

Nevertheless, some considerations have to be done in order to better understand our results. Usability research is considered behaviour-driven: you observe what people do, not what they say. In contrast, market research is largely opinion-driven: you ask people what they think. Behaviour-driven research is more predictable. Different studies supporting the assumption argued that just 5 participants could reveal about 80% of all usability problems that exist in a product (Virzi, 1992; Landauer and Nielsen, 1993;

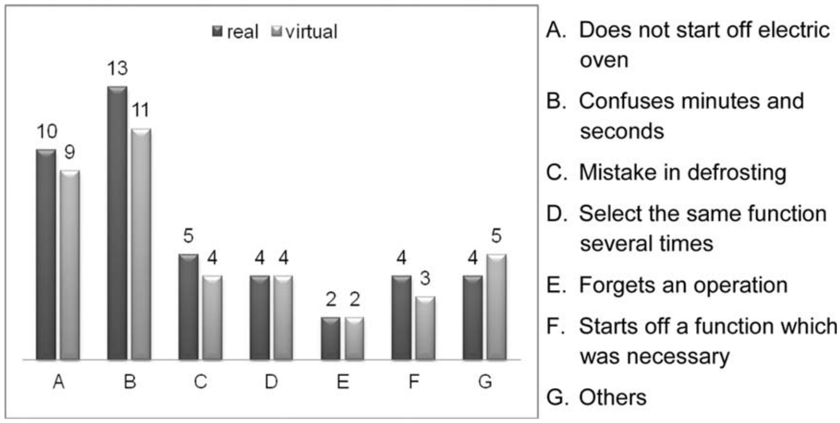

Fig. 6. Error typologies and their frequency during the test.

Table 2
One-way ANOVA table for degree of satisfaction.

		Mean	Std. dev.	*F*	Sig.
1. Easiness of task	Sample *A*	4.00	0.667	2.65	**0.121**
	Sample *B*	4.50	0.707		
	Total	4.25	0.716		
2. How agreeable the product was	Sample *A*	3.80	0.789	1.8	**0.196**
	Sample *B*	3.40	0.516		
	Total	3.60	0.681		
3. Frustration while using product	Sample *A*	1.40	0.699	0.0	**1.0**
	Sample *B*	1.40	0.516		
	Total	1.40	0.598		
4. Clarity and simplicity of use	Sample *A*	4.00	0.667	3.46	**0.079**
	Sample *B*	4.50	0.527		
	Total	4.25	0.639		

Nielsen, 2000). As consequence, we have used samples with 10–15 users in our tests and an alpha level of 0.1 in the analysis of variances.

Table 1 allows one to compare the number of errors made by the two samples of users (*A* and *B*) while carrying out the tests. The difference between the two mean values for the four tasks is not statistically significant. On the other hand, after having carefully analysed the most significant typologies of mistakes made by the two samples of users during the tests (Fig. 6), we clearly noted that the virtual interface does not distort the understanding of the product interface. In fact, Fig. 6 shows that number and typologies of mistakes are the same for real and virtual experiment.

Starting from these results, we can affirm that the virtual interface does not increase difficulties in understanding while carrying out the tasks, and it does not distort the effectiveness of the system.

In other words, we can accept the null hypothesis since there are no significant differences among the samples, or else the number of errors is not dependent by the type of experiment (real or virtual) carried out by each sample.

The observation of users during the execution of tasks (supported by a video camera used to film the development of tests) and the analysis of satisfaction questionnaires were very useful in determining the ''degree of satisfaction'' and in the evaluation of unease felt while facing the product interface. Also in this case, the ANOVA analysis we carried out showed how the degree of satisfaction of the two samples of users was not statistically significant. The latter (ranging from 0 = low to 5 = high) was not affected by the experiments (real or virtual). In particular, the results of the four questions are summarised in Table 2.

Only for question 4 (*Clarity and simplicity of use*), the difference of the two mean values (4.0 vs. 4.5) is statistically significant: the lack of haptic devices (as evidenced by video registrations and users feedback) makes it more difficult to use the virtual interface.

As far as completion time is concerned, the experiment points out longer execution times for sample *B* (on average twice as much) than the average times registered by sample *A* (Table 3). As stated above, the longer execution times are mainly due to difficulties in using the virtual interface, because of the different perception one has of the product.

Table 3
One-way ANOVA tables for task completion times.

		Sum of squares	Df	Mean square	F	Sig.
Task 1	Between groups	1584.200	1	1584.20	27.055	**0.0**
	Within groups	1054.000	18	58.56		
	Total	2638.200	19			
Task 2	Between groups	2205.000	1	2205.00	21.491	**0.0**
	Within groups	1846.800	18	102.60		
	Total	4051.800	19			
Task 3	Between groups	4410.450	1	4410.45	23.585	**0.0**
	Within groups	3366.100	18	187.01		
	Total	7776.550	19			
Task 4	Between groups	8120.450	1	8120.45	50.942	**0.0**
	Within groups	2869.300	18	159.41		
	Total	10,989.750	19			

		N	Mean (s)	Std. dev.	Std. error	Lower bound	Upper bound	Min	Max
Task 1	Sample A	10	39.40	9.652	3.052	32.50	46.30	30	61
	Sample B	10	57.20	4.894	1.548	53.70	60.70	53	70
	Total	20	48.30	11.784	2.635	42.79	53.81	30	70
Task 2	Sample A	10	51.60	3.627	1.147	49.01	54.19	46	56
	Sample B	10	72.60	13.858	4.382	62.69	82.51	56	95
	Total	20	62.10	14.603	3.265	55.27	68.93	46	95
Task 3	Sample A	10	37.30	3.335	1.055	34.91	39.69	32	42
	Sample B	10	67.00	19.050	6.024	53.37	80.63	56	105
	Total	20	52.15	20.231	4.524	42.68	61.62	32	105
Task 4	Sample A	10	52.10	2.283	0.722	50.47	53.73	49	56
	Sample B	10	92.40	17.709	5.600	79.73	105.07	58	104
	Total	20	72.25	24.050	5.378	60.99	83.51	49	104

The main cause of delays in completing tasks was the difficulty in using the virtual knob to set the time on the oven.

The data obtained through this test show a particular analogy between the two samples (A and B), mainly as far as types and number of mistakes made while carrying out the tasks are concerned. On the other hand, the main limits of our system depend on the perception of the virtual product (typical limits in an immersive VE, since they are due to a lack of tactile feedback and to inaccuracies of the input devices one uses).

However, the results obtained lead us to believe that this experimental approach is a valid alternative to traditional methods for product interface usability evaluation and that the interaction with the virtual interface does not invalidate the usability evaluation itself. The proof of the truthfulness of the statements above is the fact that, regardless of the type of interaction taken into consideration (whether real or virtual), the same difficulties of functional understanding of the product were noticed in all users.

5. Study 2: efficacy of focus group in the analysis of virtual products

5.1. Experimental task and participants

We planned the second study to test the efficacy of VP4PaD to redesign the user interface of an existing product by means of users' involvement in a focus group. Since the direct use of VR tools may not be accepted by the end users, we have tried to adopt VP4PaD to conduct focus groups analyses where an operator interacts with the virtual prototype while the users' group observes and judges the functionalities and the behaviour of the product interface. In this experiment, we have employed a focus group to collect suggestions and ideas on possible improvements of the interface of an existing product (the microwave oven described in the previous section) reproduced through a virtual prototype. The product interface has been redesigned taking into account the data collected from the focus group analysis. To evaluate the efficacy of using VP4PaD with a focus group, we have compared the results of two usability tests: the first one realised with the original interface; the second one realised with the redesigned interface.

In order to carry out this study, we chose two new samples of participants as well as the test results of sample ***B*** mentioned in the previous section, that carried out the usability test with the commercial interface. The first sample of users F (F_1, …, F_{10}), included 10 participants aged 35–45 (8 females and 2 males), in which all participants were also classified, according to their experience with microwave ovens, expert users. This sample was involved to carry out the focus group, in order to identify the requirements of a new interface of a microwave oven. The second sample of users

C (C_1, …, C_{10}), with the same characteristics as sample ***B***, was asked to assess the usability of the new designed interface.

5.2. Experimental design and procedure

The whole experiment was carried out in a VE, using virtual interfaces modelled into VP4PaD. The experiment was subdivided into four steps:

1. focus group with sample *F*
2. analysis of results and redesign of microwave oven interface,
3. usability tests in VE with redesigned interface (sample ***C***),
4. results of the comparison between commercial interface and redesigned interface.

At first, a focus group was conducted using the virtual interface of a commercial product. Thanks to this procedure, an experienced operator showed the participants how to use the interface. The focus group was carried out in three phases:

- The operator carried out three tasks to show users how the interface worked;
- The participants repeated the tasks by using a drawing of the interface;
- The users filled in a questionnaire on the interface (efficiency perceived, comprehensibility, facility of use, satisfaction, etc.).

These three phases were followed by an open discussion (which was also video recorded) on the functioning of the interface (Fig. 7).

The focus group supplied us with two kinds of results: some verbal suggestions (that were recorded) and a series of graphs concerning number of errors and error typologies.

Subsequently, we redesigned the interface starting from suggestions made by the focus group. And the third step was the usability test, that was carried out by observing the sample *C* during their interaction with the virtual interface. The activities were the same as the ones described in Section 4.2.

Finally, we compared the results of sample *B* with the results of sample *C*.

5.3. Results

The main purpose of the present study is the development and evaluation of a product interface design practice in VE that supports a more effective user/designer cooperation. For this reason, we are more interested in evaluating the improvement of the usability of redesigned interfaces compared to commercial interfaces used as references (Fig. 8a) rather than making quantitative judgements on the degree of usability of the interfaces themselves.

The analysis of the results is focused on suggestions obtained from focus groups that we summarise in:

- time display not clear and ambiguous,
- function keys not easily identifiable,
- general layout improvement.

Starting from these suggestions, we redesigned a new interface (Fig. 8b), in which the most important features implemented are:

Fig. 8. (a) Commercial (reference) interface and (b) redesigned interface.

Fig. 7. Focus group with the virtual prototype.

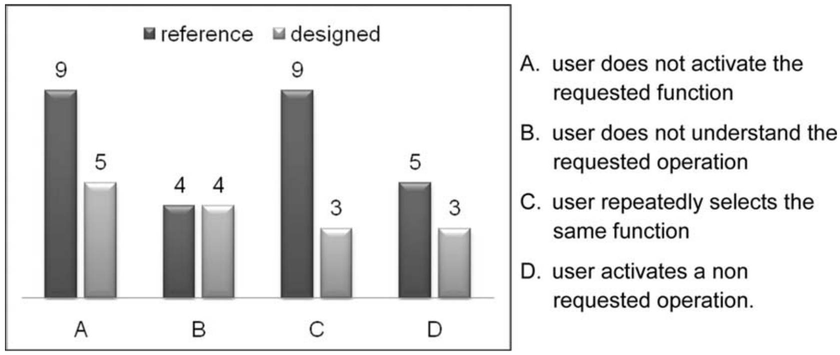

Fig. 9. Error typologies and their frequency during the test.

Table 4
One-way ANOVA tables for number of errors.

		Sum of squares	Df	Mean square	F	Sig.
Task 1	Between groups	0.3	1	0.300	1.800	**0.272**
	Within groups	0.5	3	0.167		
	Total	0.8	4			
Task 2	Between groups	1.648	1	1.648	5.288	**0.042**
	Within groups	3.429	11	0.312		
	Total	5.077	12			
Task 3	Between groups	0.107	1	0.107	0.714	**0.437**
	Within groups	0.750	5	0.150		
	Total	0.857	6			
Task 4	Between groups	1.250	1	1.250	3.082	**0.096**
	Within groups	7.300	18	0.406		
	Total	8.550	19			

		N	Mean	Std. dev.	Std. error	Lower bound	Upper bound	Min	Max
Task 1	Sample B	2	1.50	0.707	0.500	−4.85	7.85	1	2
	Sample C	3	1.00	0.000	0.000	1.00	1.00	1	1
	Total	5	1.20	0.447	0.200	0.64	1.76	1	2
Task 2	Sample B	7	1.71	0.756	0.286	1.02	2.41	1	3
	Sample C	6	1.00	0.000	0.000	1.00	1.00	1	1
	Total	13	1.38	0.650	0.180	0.99	1.78	1	3
Task 3	Sample B	4	1.25	0.500	0.250	0.45	2.05	1	2
	Sample C	3	1.00	0.000	0.000	1.00	1.00	1	1
	Total	7	1.14	0.378	0.143	0.79	1.49	1	2
Task 4	Sample B	10	1.60	0.843	0.267	1.00	2.20	1	3
	Sample C	10	1.10	0.316	0.100	0.87	1.33	1	2
	Total	20	1.35	0.671	0.150	1.04	1.66	1	3

- redesign of time display (separation between seconds, minutes and hours),
- separation between function keys (using different colour and different layout),
- grouping of incremental/decremental functions (power, temperature, weight).

Fig. 9 and Tables 4 and 5 show some of the most significant data for the assessment of the usability of the two interfaces. We compared the results obtained in the previous section with the sample B and the results of sample C who tested the new interface.

The graph in Fig. 9 allows one to compare the total number of mistakes (grouped according to typology) made by the two samples of users while carrying out the test.

The analyses of variances (ANOVA) were used to analyse the experimental data (task completion time and number of errors). In Table 4, it is possible to see that only tasks 2 and 4 are statistically significant (F_{T2} (5.288) = 0.042, $p < 0.1$–F_{T4} (3.082) = 0.096, $p < 0.1$). This is due to the fact that only during the execution of such tasks the users used the display, which represents the most significant modification of our new interface.

In regards to task completion times, Table 5 shows that all results are statistically significant. Moreover, the table shows how the sample B registered longer average execution times than the average times registered by the sample C. This result is due to the better usability of the redesigned interface that has allowed to reduce the completion times (i.e. the new interface is more efficient (ISO/DIS 9241-11)).

Table 5
One-way ANOVA tables for task completion times.

		Sum of squares	Df	Mean square	F	**Sig.**
Task 1	Between groups	92.450	1	92.450	3.185	**0.091**
	Within groups	522.500	18	29.028		
	Total	614.950	19			
Task 2	Between groups	1767.200	1	1767.200	11.905	**0.003**
	Within groups	2672.000	18	148.444		
	Total	4439.200	19			
Task 3	Between groups	561.800	1	561.800	2.917	**0.105**
	Within groups	3466.400	18	192.578		
	Total	4028.200	19			
Task 4	Between groups	3200.450	1	3200.450	14.744	**0.001**
	Within groups	3907.300	18	217.072		
	Total	7107.750	19			

		N	Mean (s)	Std. dev.	Std. error	Lower bound	Upper bound	Min	Max
Task 1	Sample *B*	10	57.20	4.894	1.548	53.70	60.70	53	70
	Sample *C*	10	52.90	5.840	1.847	48.72	57.08	44	63
	Total	20	55.05	5.689	1.272	52.39	57.71	44	70
Task 2	Sample *B*	10	72.60	13.858	4.382	62.69	82.51	56	95
	Sample *C*	10	53.80	10.239	3.238	46.48	61.12	40	65
	Total	20	63.20	15.285	3.418	56.05	70.35	40	95
Task 3	Sample *B*	10	67.00	19.050	6.024	53.37	80.63	56	105
	Sample *C*	10	56.40	4.719	1.492	53.02	59.78	50	65
	Total	20	61.70	14.561	3.256	54.89	68.51	50	105
Task 4	Sample *B*	10	92.40	17.709	5.600	79.73	105.07	58	104
	Sample *C*	10	67.10	10.979	3.472	59.25	74.95	52	80
	Total	20	79.75	19.341	4.325	70.70	88.80	52	104

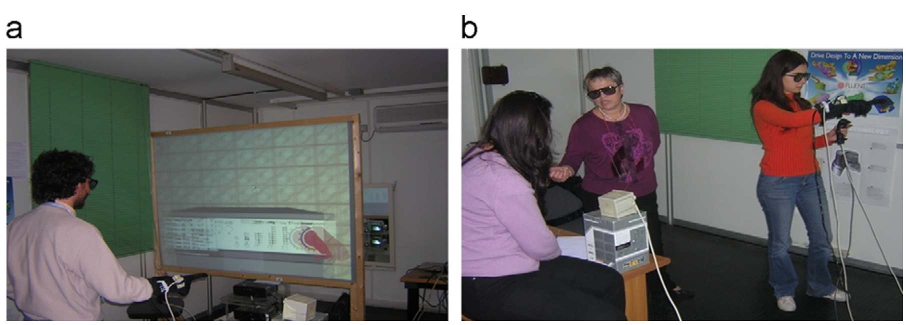

Fig. 10. Different ways of carrying out a sketch session: (a) without an operator and (b) with an operator.

From the results above one can infer that the redesigned interface has a better degree of usability than the commercial interface; both the number of mistakes and the task completion times are always the lowest when users use the redesigned interface. In keeping with our goal (the evaluation of a product interface design practice in VE), the results confirm the validity of our experiment.

6. Study 3: efficacy of the users as co-designers with VP4PaD

6.1. Experimental task and participants

"*The ideal participation involves customers as co-designers*" (Reich et al., 1996). In this study, we want to evaluate how VP4PaD may support the direct involvement of the end users as co-designers, giving them the possibility to sketch the product interface and immediately test its functionalities (Bruno et al., 2007). In this experiment, designers and users collaborate in order to define a new interface of a washing machine.

Through the direct interaction with a 3D model of the product, we aim to:

1. gather more information regarding the user's expectations as concerns the product that is being designed;
2. facilitate the involvement of end users in the initial design phases, and, in particular, during the product conceptualisation phase.

Also for this experiment, in order to validate our procedure, we have compared the results from two usability tests: the first one realised with the "virtual" interface of a commercial washing machine; the second one realised with a new interface designed beginning from user's sketches.

The experiment was tested on three samples of users. The first sample of users D ($D_1, \ldots, D_{15}$) of 15 participants modelled 15 washing machine interfaces using VP4PaD. The sample included 5 inexperienced users with little knowledge of washing machines and 10 more experienced users with a good knowledge of the electrical appliance. The group of inexperienced users, formed by young graduates aged 25–30 with good computer skills, used VP4PaD in person, and the interaction with the virtual prototype took place after having shortly practiced using VR devices (Fig. 10a). The expert users, formed by women aged between 30 and 50, used the system with the technical support of an experienced operator who carried out the functions that were verbally given to him/her by the user (Fig. 10b).

The second and third sample, respectively, L ($L_1, \ldots, L_{10}$) and M ($M_1, \ldots, M_{10}$), both with 10 participants, were asked to carry out the usability test with, respectively, a commercial washing machine interface and a redesigned washing machine interface. For this experiment, we chose 20 students with the same characteristics described in Section 4.1. All participants had a good experience in using a washing machine.

6.2. Experimental design and procedure

Also for this case, the whole experiment was carried out in a VE using VP4PaD. The experiment was structured as follows:

1. Sketching of washing machine interfaces: The users of the first sample D modelled the interface through the choice of knobs–buttons–switches by VP4PaD. The result was the creation of 15 washing machine interfaces that reflect the aesthetic and functional opinions of the users.
2. Usability test: Since the obtained interfaces were in working order, each user tested the interface to assess usability. Subsequently, the user was given the possibility to modify the proposed interface.
3. Redefinition of the interface requirements: After having listened to and observed users and analysed the results, we gathered new specifications based on the user's requirements and the functions he/she prefers. We also gathered information on the typology and disposition of buttons/knobs. Thanks to these results, we redefined a new set of requirements.
4. Designing a new command panel for the washing machine.

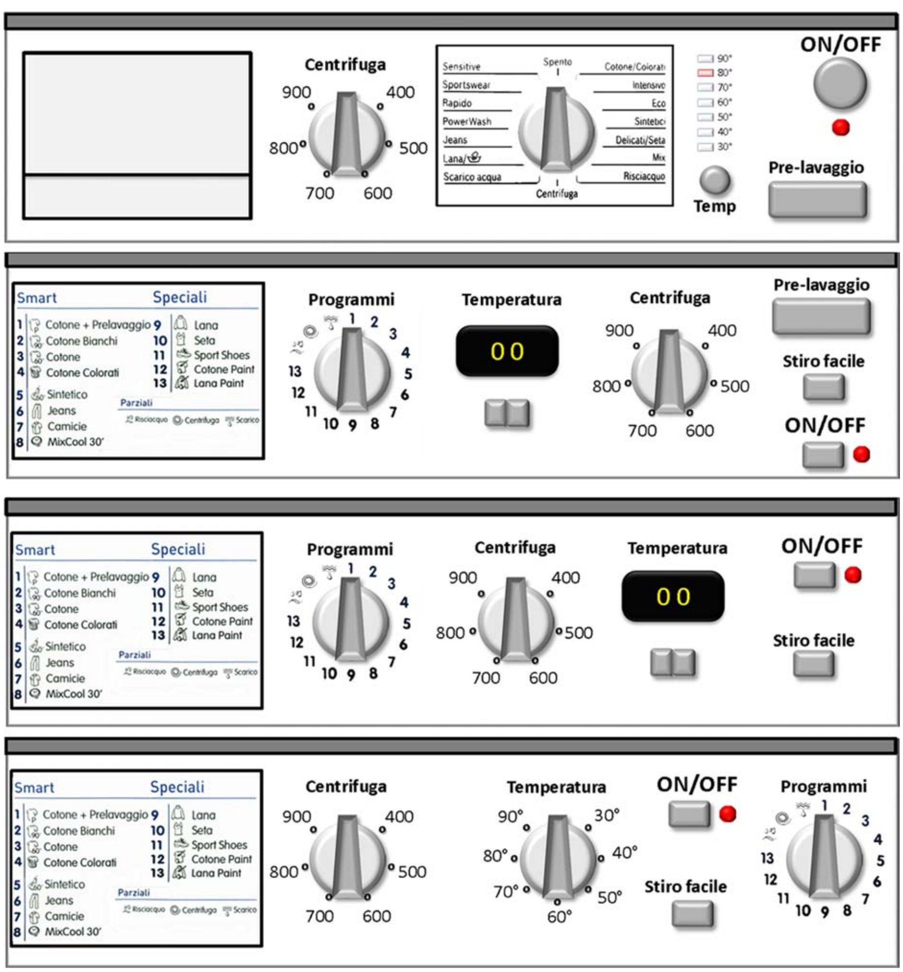

Fig. 11. Some of the 15 interfaces designed by the users.

5. Usability test: The new panel was compared to the interface of a washing machine currently on the market, through a usability test. Samples *L* and *M* (with experience in using washing machines) carried out the usability test, in keeping with the procedures described in the previous section.
6. Analysis of the results: The designed interface was compared to reference interfaces (of a commercial washing machine), in order to validate the effectiveness of the proposed methodology.

In order to gather as much information as possible, notes were taken on all comments made, the whole activity was recorded and a file containing all significant passages of the definition of the interface was memorised.

6.3. Results

The articulation of the experiment determined different results. At the end of the step 1, 15 interfaces were modelled (Fig. 11). The sets of knobs, buttons and switches had been previously selected by the authors and they were limited in number and in functions. Hence, the modelled interfaces express only some aspects of the interface like general layout, colour and size of buttons and knobs.

Nevertheless, all collected data was useful to design a new interface for the washing machine. In particular, the most common suggestions were:

- the use of a knob for wash programmes;
- to put start/stop button in a prominent place;
- the use of a straightforward programme panel;
- the use of digital buttons to control temperature and defer programmes.

In keeping with the suggestions above we redesigned a washing machine interface (Fig. 12a). Later, we have modelled, in VP4PaD, a commercial interface as a reference in usability test (Fig. 12b).

A new usability test was carried out with these two interfaces (the activities were the same as the ones described in Section 4.2).

Tables 6 and 7 show the most significant data for the assessment of the usability of the two interfaces. We compared the results obtained from sample *L* and the results of sample *M* who tested the new interface.

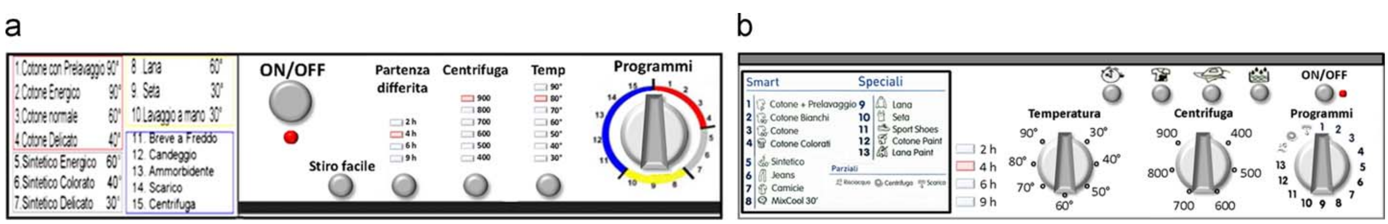

Fig. 12. (a) Designed interface and (b) commercial (reference) interface.

Table 6
One-way ANOVA tables for number of errors.

		Sum of squares	Df	Mean square	*F*	Sig.
Task 1	Between groups	0.533	1	0.533	2.667	**0.178**
	Within groups	0.800	4	0.200		
	Total	1.333	5			
Task 2	Between groups	1.500	1	1.500	3.000	**0.333**
	Within groups	0.500	1	0.500		
	Total	2.000	2			
Task 3	Between groups	0.300	1	0.300	1.800	**0.272**
	Within groups	0.500	3	0.167		
	Total	0.800	4			

		N	Mean	Std. dev.	Std. error	Lower bound	Upper bound	Min	Max
Task 1	Sample *L*	5	1.20	0.447	0.200	0.64	1.76	1	2
	Sample *M*	1	2.00	.	.	.	.	2	2
	Total	6	1.33	0.516	0.211	0.79	1.88	1	2
Task 2	Sample *L*	2	2.50	0.707	0.500	−3.85	8.85	2	3
	Sample *M*	1	1.00	.	.	.	.	1	1
	Total	3	2.00	1.000	0.577	−0.48	4.48	1	3
Task 3	Sample *L*	2	1.50	0.707	0.500	−4.85	7.85	1	2
	Sample *M*	3	1.00	0.000	0.000	1.00	1.00	1	1
	Total	5	1.20	0.447	0.200	0.64	1.76	1	2

Table 7
One-way ANOVA tables for task completion times.

		Sum of squares	Df	Mean square	F	Sig.
Task 1	Between groups	510.050	1	510.050	8.670	**0.009**
	Within groups	1058.900	18	58.828		
	Total	1568.950	19			
Task 2	Between groups	832.050	1	832.050	8.363	**0.010**
	Within groups	1790.900	18	99.494		
	Total	2622.950	19			
Task 3	Between groups	638.450	1	638.450	3.489	**0.078**
	Within groups	3294.100	18	183.006		
	Total	3932.550	19			

		N	Mean (s)	Std. dev.	Std. error	Lower bound	Upper bound	Min	Max
Task 1	Sample L	10	65.00	8.551	2.704	58.88	71.12	53	80
	Sample M	10	54.90	6.674	2.111	50.13	59.67	45	68
	Total	20	59.95	9.087	2.032	55.70	64.20	45	80
Task 2	Sample L	10	68.00	11.528	3.645	59.75	76.25	54	86
	Sample M	10	55.10	8.130	2.571	49.28	60.92	44	66
	Total	20	61.55	11.749	2.627	56.05	67.05	44	86
Task 3	Sample L	10	76.00	15.937	5.040	64.60	87.40	57	105
	Sample M	10	64.70	10.584	3.347	57.13	72.27	51	82
	Total	20	70.35	14.387	3.217	63.62	77.08	51	105

This experiment led to two contrasting results: on one hand, the number of errors was too limited for it to be considered statistically significant (Table 6: 6 mistakes for task 1, 3 for task 2 and 5 for task 3). On the other hand, we reached statistically significant results as far as task completion times are concerned (Table 7).

Even though it is only possible to refer to the efficiency of the interface (related to the completion time task (ISO/DIS 9241-11)) and not to the effectiveness of the solution (related to the number of mistakes), we can affirm that the PD has had positive effects on interface usability. The results are, in fact, more favourable to redesigned interfaces than to commercial ones. But, above all, we would like to point out the significant improvement one may obtain thanks to the proposed methodology.

7. Conclusions

Although VR has been used in several research studies as a support tool for PD, it has been scarcely used in the industrial field and, if we analyse literature, we may clearly see that hardly any studies consider the possibility of employing VR in the design of industrial product interfaces. For this reason, we decided to define a PD approach, able to support designers in the involvement of end users in the product interface design. We also implemented a specific VR tool that helps us to test and validate this approach through three different experiments, involving 75 persons, divided into five different usability tests, one focus group and one co-design test.

The results of the first experiment led us to believe that VR is a valid alternative to traditional methods for product interface usability evaluation and that the interaction with the virtual interface does not invalidate the usability evaluation itself.

After this validation of VR in a usability test, we evaluated the efficacy of the methodology and the tools we propose. The results of the second experiment demonstrate that users are able to evaluate the usability of a product also through a virtual prototype, and that it is possible to analyse problems and to collect suggestions from the users, in order to improve the product interface. The results of the last experiments put in evidence that it is possible to involve the end users during the design process and to produce an improvement of the interface usability.

As concerns the limits of our approach, we must point out mainly two aspects. The first is an intrinsic limit to the PD approach: observing users outside of their daily context may lead to a variation of the modes of interaction with the product. Whereas, the second aspect is connected to the lack of haptic devices during the interaction with the interface. It is a limit of our system because we cannot evaluate the real dexterity and/or the level of force required to make a selection, but we can only assess efficacy, efficiency and satisfaction of use related to the understandability of the product interface. Starting from this consideration we are currently developing a VR environment that integrates haptic devices and we plan to evaluate in future tests, the benefits related to the presence of force feedback.

Lastly, we report some considerations concerning the choice of sample of users and the choice of type of interface. Young users with good computer skills are preferable because they can directly interact with the virtual interface, while the elderly users require the technical support of an experienced operator. Moreover, the young users are enthusiastic to carry out the test because they are attracted by tests with the VR tools; this simplifies the recruiting of users for the experiments. Referring to the type of interface, we can assert that in VR the interaction through buttons, levers and display is easier compared to the knobs because it is more complicate to recognise the movement of the wrist using the data glove.

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