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THE IMPACT OF VIRTUAL ENVIRONMENTS ON HUMAN COLLABORATION IN PRODUCT DESIGN

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ABSTRACT

Virtual Reality (VR) has quickly evolved over the last years in terms of technological and applicative dimensions. Human-Computer Interaction is particularly meaningful in the design activities involving multidisciplinary teamwork, collaborating to achieve a common task. It influences users behaviors, representational and communication modalities. A successful Collaborative Virtual Environment has to naturally support cognitive design actions while reducing time and costs. In this context, our research goal is to evaluate performances of different human-scale virtual environments in design situations involving multiple specialists with different knowledge and expertise. We proposed a protocol to highlight the main interaction styles in collaborative environments in order to assess how VR systems affect multidisciplinary cooperation. Experimental test cases are used to compare performances of virtual and physical prototypes in design reviews activities.

Keywords: Collaborative design, Multimodal interaction, Virtual Reality, CVE

1 INTRODUCTION

Product design aims at creating artifacts satisfying all customers needs and improving people's lives. It is an iterative process that consists into a set of complex and multidisciplinary activities. Communication problems can emerge due to different skills and competences.

In the recent years, new Human-Computer Interfaces (HCI), from Virtual Reality (VR), to Augmented Reality (AR) and Mixed Reality (MR), till Tangible User Interfaces (TUI) have been introduced in the product development process to support models visualization and participants interaction in a shared human-scale virtual environment. These technologies are able to provide multimodal interaction by supporting communication through different sensory modalities while carrying meaning through a representational modality, mainly virtual prototypes. In several industrial contexts, human-scale virtual environments and virtual prototyping (VP) are progressively replacing traditional desktop-based systems. Time savings, costly physical prototypes reduction and collaboration improvements are some of the well-known benefits derived from VR adoption. In order to successfully achieve technologies integration, we state that virtual environments and VP have to naturally support cognitive design actions and follow users' natural communication styles by stimulating comparison and discussion while providing the best benefits. Interaction in collaborative teamwork has already been studied in literature as described in section 2: theoretical models are presented to analyze the interaction between humans and virtual mock-ups but no indications are given about either technological or actors' performance assessment. Few research works recognize changes occurred in traditional design styles and investigate the effect of different virtual environments on real design reviews activities. Some effort has been spent in protocol analysis but no one correlates the obtained results with technologies performances in order to address technological upgrades and future research.

Nowadays some questions remain yet unsolved: is really the well known co-located collaboration on VP more efficient than the traditional one carried out on physical prototypes? Can traditional product representations be substituted by digital design media without any effect on users' performances?

In this context, our research goal is to evaluate the performance of different human-scale virtual environments in different design situations involving multiple specialists with different knowledge and expertise. We proposed a protocol to highlight the main cognitive actions and interaction styles in collaborative environments in order to assess how VR systems affect human behaviors, design practice and multidisciplinary cooperation. VR is chosen as it is the most widespread system in real industrial design contexts.

The proposed objective falls in a long-term research work that aims at assessing human-scale virtual environments performances at different levels:

- derived benefits from VR applications in terms of time to market, costs reduction and product quality [1];
- VR-based interfaces usability, presence and depth of sensations experienced by users performing specific product design tasks [2], [3];
- users behaviors in VR-based collaborative environments.

Initial goals have been already achieved, structured methods have been proposed and preliminary research results have been presented. The paper focuses on the third objective in order to define an ideal collaborative virtual environment (CVE) and set a roadmap for improving human-computer interaction. After analyzing the design process and identifying the main collaborative dimensions, the conceptual design collaboration is deepen as it is considered the most critical phase for product development. After defining a theoretical model of interaction, the paper describes the proposed protocol for design reviews investigation and observation. In order to collect significant results in accord with the research goals, it is applied to a real industrial design case where physical and virtual prototyping is used to support conceptual design collaboration. Experimental results emerging from protocol analysis application are then discussed. They allow setting future research work.

2 RELATED WORK

Collaborative design requires creating effective collaborative virtual environments to share and manage the whole design knowledge flow. As the development of the extended enterprise requires new tools to manage the distributed knowledge and the interaction among the design and supply chains (i.e. web conferencing, data sharing, instant messaging, etc.), the creation of effective Virtual Teamwork by Information Communication Technologies (ICT) represents a wide explored issue to implement collaborative networked organizations (CNO). Researches mainly focus on the development of new tools and organizational models to reduce the gaps between virtual teamwork and face-to-face collaboration [4], [5]. However, in synchronous collaboration, face-to-face meetings remains a preferred mode of interaction during decision-making activities that can be supported by VR-based technologies to facilitate product evaluation on virtual prototypes and human interaction. Numerous case studies focus on the application of VR-based technologies in supporting the early stages of the product development, where the teamwork dimension is central. Their implementation implies several difficulties related to systems integration, tools flexibility, knowledge capitalization and data traceability. In this context, research mainly addresses hardware-software issues in order to elaborate different systems solutions. They propose synthetic environments characterized by distributed knowledge management tools and dynamic prototyping functionalities [6], [7].

The emergent need for novel HCI stimulates researchers in understanding users interaction with tools and systems. Although systems usability poorly considers interaction between users while performing a design task, some examples face this aspect. Kaur et al. [8] have developed a guidance for understanding user actions inside virtual environments that considers task-goal oriented, exploratory and reactive modes of behavior. Anyway a theoretical model has been proposed and results remained at a predictive level. A more concrete example is represented by He and Han [9]. They proposed a human-centered collaborative tool to support human-human interaction. The proposed platform is classified as desktop-based as the instant collaboration tool is defined and implemented for 3D heterogeneous CAD applications.

Few limited works recognize the impact of VR tools on design communication styles and teamwork dynamics. Recently a growing attention has been focused on TUIs that represent an alternative to traditional human-computer interfaces such as keyboards, mouse and large volume vertical screens. According to Seichter and Kvan [10] TUIs are sort of media between real and perceived affordances stimulated by the interface physical properties and by the digital behaviors of the displayed objects. In the context of TUI, some efforts have been done to demonstrate how they affect designers spatial cognition during design review sessions [11] [12].

3 COLLABORATION IN THE PRODUCT DEVELOPMENT PROCESS

Competitiveness forces companies to seek ways to constantly develop innovative products able to provide customers with increased functionalities, technical, aesthetic and ergonomic performances.

The simultaneous involvement of multiple aspects in product design requires the participation of multidisciplinary teamwork with a high degree of specialization to manage the growing products complexity. In order to reduce time to market team communication, knowledge transfer, data sharing should be supported by proper tools and methods. Teamwork efficiency can be achieved by correlating different representational modalities with specific collaborative tasks [13].
By analyzing a typical product development process, we can identify five different collaborative dimensions characterized by specific activities, actors and requirements (Table 1).

Table 1. The identified collaborative dimensions in product development

Strategic	it is the first collaborative stage of the project and involves the top management and project managers. The company's decision making group analyzes different product ideas and chooses which one better answers to the product brief requirements in order to direct further developments. Product ideas are usually presented by photorealistic rendering images, digital models and generic presentations even if they are still abstract and unstructured. Decisions are made on emotional impressions and mutual perceptions. Face-to-face meetings are the most adopted way of communication.
Conceptual	it is based on continuous design reviews (DRs) on product prototypes in order to achieve the final product design concept coherently with initial requirements. The primary technical feasibility is generally carried out. Prototypes can be either physical or virtual depending on the adopted design media and participants skills. DRs generally involve marketing staff, technical managers and styling designers, who usually elaborate different conceptual alternatives on the basis of the previous company's decisions. This is the first decision-making activity. In this collaborative dimension individual work is evaluated and decisions for future work are taken: meeting collaboration is bidirectional and active. Shared visualizations, on-demand models sections, views, and mark-ups have a great importance for tasks completion.
Advanced	it is based on iterative DRs on advanced product models, in order to engineer the validated product shape and to generate the final technical documentation. Design solutions are described by detailed drawings and 3D CAD models previously submitted to different simulations (structural, thermal, fluid dynamical, manufacturing, molding, assembly-disassembly verifications, etc.). This phase involves company's technical and manufacturing engineers and suppliers. Co-design activities with the supply-chain introduce new collaboration features and communication styles. Advanced DRs mainly requires work at the individual dimension. Data collection and traceability, project monitoring and scheduling, links between 2D drawings and suppliers' quotations are crucial for successfully achieving the process tasks.
Interplay	it supports all previous collaboration dimensions as it spreads along the whole design cycle. The design teamwork reviews individual outcomes making decisions about their correspondence to design goals. It does not require face-to-face collaboration and can be carried out in remote modality. Efficient data distribution, fast and safe data sharing, mark-ups and annotations are the main needs. Interplay collaboration characterizes activities as equipment design, standard components engineering, etc.

Investigations in several industrial design contexts reveal that the conceptual design collaboration is particularly crucial for the design process efficiency as participating actors have different backgrounds. Moreover, at this stage, physical prototyping is difficult to be replaced for the specific skill of the involved styling designers who prefer to free-hand sketch and tangibly interact with product models. CVEs can be considered efficient in accord with conceptual design collaboration tasks only if they provide participants with interaction styles as similar as physical prototyping [14].

4 THE PROTOCOL TO ASSESS THE IMPACT OF VR SYSTEMS ON DESIGN COLLABORATION

Protocol analysis has been accepted as a prevailing experimental technique for exploring human interaction and getting access to designers and engineers at work. Protocol approaches used in design research can be classified into two categories: concurrent protocols and retrospective protocols. Generally, concurrent protocols are used when focusing on the process-oriented aspect of designing, and information processing view, whereas retrospective protocols are utilized when focusing on the content-oriented and cognitive aspects of design concerning with the notion of reflection in action.
Our study is an adaptation of the protocol analysis approach that consists of data collection by different observation techniques, data segmentation, coding and analysis.
Once working sessions have been recorded and data collected, we divided the protocol data into small segments where each segment is then assigned codes that characterize different categories of metrics, as well described at section 4.2. Two experts in human computer interaction and in industrial processes have been involved to analyze the collected data, to segment the recorded sessions and to assign a value for each metric related both to codes occurrences and time. The proposed coding scheme is just an attempt to investigate collaborative teamwork. The reliability of the coding is

partially obtained by comparing the values obtained by analyzing different working sessions that are related to different projects and that involved different actors.

4.1 A cognitive model to analyze the teamwork collaboration

As previously described, DRs repetitively occur during the design process and their features depend on which collaborative dimension they belong to. All DR sessions objectives are: to identify at-risk areas, real and potential, for every project aspect, to establish the level of risk and the solving priority for each of them, to recognize the influence of every aspect has on the final project objectives, to propose possible solutions. DRs differ from simple design outcomes presentations as the goal is not to illustrate the final solution but to discuss it and decide how make it real. Collaboration requires continuously shifting from the individual to the team dimension. The second is characterized by active interaction, direct communication and share understanding, while individual dimension is supported by data sharing and information interchange. The team dimension can be represented by adopting the cognitive model of interaction proposed by Norman [15]. Norman's theory consists of seven stages of action and involves the explicit modeling of exploratory and reactive behaviors. Two different cycles, called gulfs, can be identified: execution and evaluation gulfs. They refer to two actions flows: "from" and "to" the world in respect of specified goals (Figure 1, at left). "The world" is represented by product models, both physical and digital, while the "goals" refer to meeting objectives.
Although participants follow different approaches depending on the supporting tools and individual skill, the recognized cognitive actions in Norman's model, representation modalities and interaction styles are similar in both traditional and virtual environments. This is due the intrinsic nature of human interaction that depends on human perception and cognition and not on the design media. Protocol analysis techniques should be adopted to explore how designers and engineers collaborate in different environments while performing the same tasks. In order to highlight the main interaction styles the proposed protocol starts from the definition of metrics as qualitative and quantitative estimates of the meaningful cognitive actions and design contents in DRs activities. They are identified in accord with the analysis scope and are not limited to the adopted experimental set-ups because they have to allow comparing different representation media impact on human actors' behavior.

4.2 Metrics for coding collaborative activities

In order to investigate moment-to-moment interaction during DRs, we have taken into account a set of control categories that can be recognized in the Norman's cognitive model of team collaboration (Figure 1, at right).

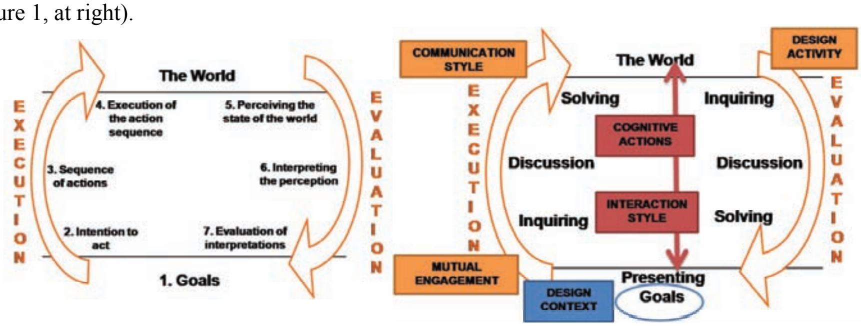


Figure 1. Norman's model of interaction (left) and the proposed categories for protocol analysis (right)

For each category a set of codes (metrics) have been defined and customized for the specific conceptual design collaboration context (Table 2):
1) Stages of the collaborative cycle derive from the cognitive model of design defined by Norman where seven main stages are defined to describe the flow of actions during design. Analyzing collaborative activities it is possible to identify four main stages that define the structure of the whole working session cycle: presenting, inquiring, discussion, solving. The first stage regards with the description of the design goals, the main outcomes, the main problems occurred during product development, etc. Different communication media can support the presentation stage: from sketches to virtual models, from conceptual diagrams to technical documentations. The second stage refers to the phase of evaluation, where participants interpret the presented "world", formulate questions in order to improve their understanding about design outcomes and ask for product design improvements and

modifications. The second stage leads to the third one as it triggers discussion among all participants. Each actor supports his/her ideas and try to find a compromise between conflicting viewpoints. The fourth stage regards with the problem-solving process and the definition of the main actions that should be executed to improve design. The analysis of their distribution allow pointing out the influence of the adopted medium of interaction.

Table 2. Protocol analysis for assessing design collaboration

CONTROL CATEGORIES			DESCRIPTION	EVALUATION METRICS	UNITS
1	*Stages of the collaborative cycle*	DA	It represents the main stages of the collaborative actions. Their distribution in time allows identifying the structure of the design cycle	P = Presentation D = Discussion I = Inquiring S = Solving	Time (min) - %
2	*Design Context*	DC	It refers to the design tasks on which participants are focusing during the 4 stages of collaborative actions	E = ergonomics M = Market A = Aesthetical T = Technical	Occurrences - %
3	*Interaction Style*	IS	It measures the modality preferred by actors for interacting with the model	1) Referring to model 2) Interacting with model 3) Simulating actions 4) Adopting different viewpoints	Occurrences - %
4	*Communication Style*	CS	It refers to the communication channel (verbal, gestural and graphical) adopted during collaboration	For verbal language: 1) Simple speech 2) Highly descriptive language 3) Emotional-introspective language For gestural marked communication: 4) Pointing gestures; 5) Representational gestures; For graphical marked communication: 6) Writing, annotating and marking-up on 3D models 7) Free-hand sketching and diagramming	Occurrences - %
5	*Mutual Engagement*	ME	It allows examining the forms of interaction that take place between participants	1) Physical orientation 2) Turnover of ideas 3) Anticipatory information 4) Attunement between participants	Occurrences
6	*Cognitive Actions*	CDA	It measures the actors' cognitive reaction to the model	*Modeling actions*: before (A), during (B) or after (C) *Perceptual actions*: n : attention to elements (A), relations (B), locations (C) *Set-up goal actions*: new (A), already known (B)	Occurrences

2) Design Contexts represents the different perspectives that can be adopted to analyze the design outcomes. Actually, during conceptual design numerous aspects need to be evaluated in order to define a product satisfying all consumers requirements: the influence of the product on the market (M), the aesthetic impact in terms of emotions and affection on consumers (A), the technical feasibility including manufacturing , functionalities, maintenance, etc. (T), ergonomics that take into consideration both usability and safety (E). The observation of the design context allows identifying which design aspects are mainly stressed during the four stages of the collaborative cycle.
3) Interaction Styles indicates the preferred modalities for interacting with product models and representations, either physical or virtual. They allow qualifying the relationship between "the world" and "goals". We identified four main interaction modalities: 1) referring to model, that happens whenever participants talk about or indicate specific product features or characteristics, 2) interacting with the model by manipulating, disassembling, touching it, etc., 3) simulating actions, that consists of emulating actions by hands or gestures without directly referring to the model, 4) changing the adopted viewpoint and position, that happens whenever different ideas simultaneously emerge on the same topic [12]. The adopted interaction styles do not refer to the collaborative concept mapping where numerous styles can be used such as co-elaboration, generation, evaluation, etc. This is due to the fact that the purpose of the study is to focus on the way of interaction with models and the main actions carried out on them.
4) Communication Styles indicates the communication channels adopted to refer to "the world" during the interaction process. The proposed communication styles are both verbal, non verbal and paraverbal. The verbal language can be 1) simple speech, 2) highly descriptive language, 3) emotional-introspective language. The main gestures that people adopt to clarify or enhance their concepts can be 4) pointing gestures that are used to refer to tasks objects and locations, and 5) representational gestures (hand shapes and movements) that are used to represent the form of the task

objects and the nature of actions to be used with those objects (for instance in simulating actions). In addition, graphical language can be used to express ideas and co-elaborate the design outcome. It consists both of 6) written texts on sketches (annotations) and digital mark-ups on 3D models and of 7) free-hand sketches and conceptual diagrams. Graphical language can be also represented via digital and hand-based means. As for verbal expression, both graphical and gestural languages can be also simple, descriptive and emotional. In the present paper, we do not consider this additional distinction.

5) Mutual Engagement allows examining the forms of interaction that take place between participants. It focuses on the level of involvement stimulated by the adopted communication media. It allows objectifying participants emotions during tasks execution and "world" evaluation. Mutual engagement can be identified by: 1) physical orientation, that consists of aptitudes in maintaining a shared interaction space and providing collaboration, 2) ideas turnover, that happens whenever a large numbers of contributions are presented and accepted, 3) anticipatory information, that consists in actions for managing the temporal structure of interaction by directly using artifacts or simple narrations, 4) attunement between participants, constituting into moment-to-moment contributions. The relevance of these metrics on mutual engagement have been discussed by a recent study [16].

6) Cognitive Actions refers to participants' cognitive reaction to product representations. They allow investigating how participants interact with models and how the adopted interfaces stimulate problem-solving processes. Cognitive actions analysis provides a key for understanding the relationship between "the world" and "goals" created by each participant. Three main cognitive actions categories have been considered: modeling, perceptual and set-up goal actions. For each of them different human behaviors have been identified and recognized in the DR process. *Modeling actions* refers to specific models modifications such as parts selection, components placement and geometrical elements re-shaping. *Perceptual actions* refer to the way designers perceive external representations and obtain useful cues for reasoning about functional issues. Actions can be referred to existing features, new elements or just discovered ones, but in all cases they can show different focus: attention to elements (A), to relations (B) or to locations (C). They entail three different behaviors. *Set-up goal actions* represent the problem-finding behavior of both designers' and engineers' and refer to cognitive activities characterizing problem-solving. Problems can be overcome by new ideas (A) or precedents solutions (B).

4.3 Observation techniques for interaction analysis

In order to measure metrics, observation techniques should be defined for monitoring DR sessions: Diary Study and Interaction Analysis (IA). Diary Study [17] supports concurrent protocol as it is adopted to to elicit information from the design process and monitor the analyzed DR inside the project context by a series of qualitative and quantitative data retrieved by the observer during collaborative work (date, project phase, previous project DRs, completed activities, number of physical prototypes, number and type of actors). IA [18] supports retrospective protocol application as it allows capturing dynamics of teamwork interaction by video recording design reviews sessions.

Due to exchanged information security, IA is performed by audio recording and simultaneously sketching on paper main gestures, positions assumed by participants, ways of interaction with design models, etc. Sketching has been considered a valid alternative to videotaping for the same level of intrusiveness and ability to record participants positions, behaviors and modes of interaction.

Neuro-Linguistic Programming (NLP) approach provides an additional investigation technique to capture non verbal communication. Cognitive models are defined to interpret human external behaviors and internal reactions. Investigation is performed by analyzing the three levels of communication, verbal, nonverbal, paraverbal, and by applying different meta-models and representing techniques (rapport, anchoring, reframing, etc.). According to NLP approach, communication involves three components: verbal messages (the words we choose), nonverbal messages (how we say the words) and paraverbal messages (our body language). Each modality has different weights in transmitting a message in teamwork: respectively 7%, 38% and 54%. The contribution of NLP approach in our protocol can be mainly recognized in the three-level structure of the investigation and the attention to particular behavioral aspects such as mirroring and reframing.

5 EXPERIMENTAL TEST

The proposed protocol has been tested on an industrial test case where product complexity makes collaboration very difficult to achieve. The partner of the research is Teuco Guzzini, an Italian

company leader in wellness products. It designs and produces showers, bathtubs, mini-pools, whirlpools, steam saunas, etc. whose design generally results from aesthetical and technical-technological features and requires multidisciplinary teamwork.
Teuco's design process completely fits that described in section 3. As mentioned before, the research attention is focused on conceptual design collaboration where products are not still developed in detail and the designer plays a fundamental role in the design solution definition.
The proposed protocol experimentations are carried out both in a traditional environment, where physical prototypes are used to explore the design solution, and in a VR-supported set-up. The objective is to identify whether and why interaction and communication modes differ inside the two contexts, which are the main differences and how VR technologies can be improved to better support human collaboration. In order to collect meaningful data, two different design cases have been tested in the two environments: they both relate to the design of an innovative bathtub provided with chromotherapy. The design tasks are similar in complexity and type and encompass alike issues: aesthetic impressions, technical and manufacturing feasibility, functions integration, etc.
The protocol has been applied in ten design review sessions, five in the VR set-up and the remaining in the traditional one. Each design review focuses on different company's innovation projects as it was not possible to monitor a single project evolution. Moreover, for a same project, both physical and virtual prototyping have been carried out, as the firsts are generally realized to supply the lacks of the seconds after the evaluation in the virtual environment.
The number of the involved users changed in accord with the project and with the design phase where conceptual collaboration takes place. However, in each session similar competences and familiarities with VP, are involved, as described below.
Differences in participants skills and teamwork sessions do not invalidate the validity of the experimental results as the analysis is mainly focused on the interaction between humans and design models, instead of the specific project goals.

5.1 Traditional vs Virtual Experimental set-ups

The two adopted experimental set-ups are described as follows (Figure 2).

Figure 2. DRs on physical prototypes (left) and on virtual ones(right)

DRs on physical prototypes generally take place in the company technical laboratory where they are realized. They are not located in a real scenario and are not made with the final materials and surface finishing. They mainly are foam models or soft prototypes. Discussion and evaluation are supported by additional representational modalities such as drawings, annotations, technical presentations, etc. Participants also use to directly sketch on the prototype surface to highlight which parts should be modified.
DRs on virtual prototypes take place in the VR Lab arranged by the company two years ago inside the technical department. It consists of a large volume display (3x2,5 m) rear projected by a DLP projector with high resolution (1400x1050). The wall is made of special Fresnel lens and the special form of prisms offers an elevated image quality. A stereo sound system provides auditory feedback. The software toolkit is composed by a commercial CAD software and a computer graphics package for virtual prototypes modeling and scene rendering, adjusting photorealistic images and managing product presentations. Sensorial multimodality is not supported: only visual and auditory feedback are provided. The system reduces immersion but increase users presence and technologies usability.
The VR Lab is used for implementing both strategic, conceptual and advanced design collaboration dimensions. During DR activities full scale virtual prototypes are shown with a high level of realism, geometrical and dimensional aspects are investigated, functional and usability analysis performed. In

particular, during conceptual design collaboration, the teamwork evaluates different design solutions by replacing taps, colors or materials, positioning the virtual prototype in different scenarios, by sketching on a digital tabletop annotating further developments, by retrieving previous product models in order to assess advances in respect with precedent DRs and monitor the project history.
In both experimental set-ups DR sessions generally involves the following competences:

- Styling Designer (SD) conceives the product shape in accord with brief specifications. He/she generally elaborates design concepts at an individual level and illustrates the design outcomes to the teamwork by different representational modalities: free-hand sketching, diagrams, foam physical mock-ups, conceptual 3D models, synthetic images. He/she is also involved in the other collaboration dimensions for the design solution validation. According to his/her abilities, the designer has a great abstraction skill and can easily predict the impact of alternative solutions on the final product design. His/her CAD-based technologies expertise is low;
- Project Manager (PM) supervises the whole product design assuming a mediation role between the marketing area, the technical one and the involved designer. He/she has a deep knowledge of market demands, competitors solutions and customers taste evolution. He/she is generally able to understand designer's language and communication codes thanks to his/her long experience with them. Interactions with product models, both physical and virtual, are mainly intuitive;
- Project Leader (PL)'s task deals with product engineering. In conceptual design collaboration he/she assesses design solutions technical feasibility. In spite of his/her technical background, he/she are able to reach a good level of abstraction. Communication with designers is not totally straightforward;
- Product Engineer (PE) assesses the manufacturing feasibility and the economic value of alternative solutions. His/her skill encompasses CAD modeling, virtual representations, Computer Aided Engineering (CAE) simulations, etc. Designer's language, both verbal and non verbal, results too abstract and difficult to understand;
- Technical or R&D Engineer (TE)'s task regards with 3D CAD modeling and technical drawings realization for production. During DRs he/she contributes to evaluate and optimize the design solution from a practical point of view participating to the materialization of the product concept. His/her limitations are related to abstraction capacity: he/she may feel difficult to understand abstract ideas because he/she need to formalize them into a structured way;
- Industrial Engineering Manager (IEM) predicts the future industrialization of the product, pointing out technological problems in achieving the intended product shape and surface finishing. His/her skill is similar to PE;
- Quality Manager (QM) occasionally contributes to conceptual design collaboration, especially when manufacturing quality can be significant for product success;
- Suppliers (S) can participate a DRs depending on the session goal. His/her skill is similar to IEM.

Differences in knowledge domains, individual skills, advanced computer-based interfaces practice make design concepts understanding difficult to achieve during DRs. As a consequence design errors and iterations occur.

5.2 Application of the experimental protocol

Diary study and Interaction Analysis are carried out in all test cases to collect data for metrics measurement. During DRs, a researcher monitors all activities by fulfilling the Diary Study MSWord format and audio recording sessions.
Information about DR's duration, adopted representational media, stored documents, content focus, participants, etc. are recorded by Diary Study (Figure 3).
Interaction Analysis was an adaptation of protocol analysis: data collection, segmentation and elaboration. Rather than ask the participants to think aloud, their conversation is recorded and transcribed, while gestures replicated by sketching them on paper. Collected data includes verbal description of design knowledge and nonverbal information such as hand and body gestures, communication style, etc. No questionnaire was used because we focus on capturing the contents of what designers do, attend to, and say while collaborating in achieving a common idea, perceiving the product models and creating new product functions. We divided the protocol data into segments according to the main performed activities.
For each segment of verbal communication, the time is transcribed and non verbal and paraverbal communications are replicated in the corresponding columns. The last column is dedicated to which

evaluation metrics can be measured for the corresponding segment (Figure 4) in order to assess occurrences and time.

Date	09/10/08
Product focus	Product line expansion , aesthetical-technical DR
Previuos DRs	2 (06/11 and 25/11)
Supporting media	CAD files from technical dept. Rendering from designers (in pdf format on CD)
Completed activities	DR1: focus on the required characteristics (same functionalities but smaller dimensions), visualization of few shape proposals by the designer. DR2: record of further observation on previous proposals, change requests to the designer.
Physical prototypes	None. Attending for realizing the first foam prototype.
Lenght of time	1h 25'
Place	Teuco's VR Lab
Actors	Designers 2 (D1 – D2) from the same design studio, Project Manager (PM), Technical Dept. Director (TD), Product Dept. Director (PD), Technical Engineer (TE), Industrial Engineer Manager (IEM)

Figure 3. Example of Diary Study fulfillment in the case of a new bathtub design.

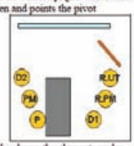
Time	Activity	Varbal analysis	Paraverbal analysis	Nonverbal analysis	DA	DC	IS	CS	ME	CDA M	CDA P	CDA S
14:40	Presentation and discussion of the first design proposal	PM: she presents the CAD model elaborated by TE and summarizes past decisions. She shows the main components and their collocation.	Firm and clear tone Descriptive language	TP: he rotates and zooms the CAD model during PM speech PM and D2 open their own drawings and technical sheets over the table	P	T	1	2		C		
		TD: he explains which technical simulations have been performed on the CAD model	Relaxed tone	TE: he rotates the model and shows only the component they are talking about in a bigger size.	P							
14:43	Analysis of the main technical problems	PM: she highlights a critical point (door opening) and describes the main problems connected with	Acute and interrogative tone		P	T	1	2			B	
		IEM: he suggests that the existing pivot's mould could be reused, so the pivot should be maintained as in the existing product version		IEM: he stands up, gets next to the screen and points the pivot	P D	T	2	4				B
		D1: he asks TE some information about the glass slope			I							
		D2-PD-IEM: they discuss about the use of the sloping glass (evaluation about aesthetical effect, cost, etc.)			D	A-T	4		2		B	
		TD: he remarks the importance of using standard pivots			D	T						
14:50	Research into design solutions for the door opening	D1: he proposes an idea that has been already applied in another project and he describes how it works "…"	The tone expresses involvement		S			3				B
		D1-TD-PD: they discuss about both the aesthetical and functional impact of the sloping glass		TE: he shows the elements under discussion	D	A	4		2-4			
		D1-TD: they accord on the characteristics of the new door opening. They joke about structural analysis	Playful tone	PM: she notes on a pad of paper	S							
14:54	Analysis of model dimensions and available spaces	PM-D2: they talk about the seating location and available spaces in the underlying structure			D	T		4-5			C	
		D1: he asks for further specifications on the pump's location and relative constraints	Interrogative and clear tone		I	T	2	2				
		TD: he asks TE to measure the areas of the present model in respect with the previous one		TD: he stands up and points the surface by touching the screen	I P		2	4				
		TE: he does not understand and ask for further details		TE: he tries to join the analyzed surfaces and looks for the geometrical inspection commands								
		TD: he deepens what he refers to										
		PM-TD: they establish how panels will be realized			S	T			2-4			B
		PM: she proposes a fresh design solution			S							
		PD: he demands for more details and explanations			I							
		PM-PD-D2: they discuss about the door opening	Firm and clear tone		D	T	2					
		IEM: he notices that a unique mould could be adopted for both versions by applying an adjustable limit switch		TE: he measures the present and the old model for comparing	S			5			B	
		TD: he asks TE to note that		TD: he stands up and simulates the hammering on the glass slab	I							
		TD-D1: they talk about breaking tests on the glass slab			D		3					
		TD: he explains how to realize the limit switch	Descriptive language	TD: he gets next the screen and points the object under discussion	P		2					
		D2: he asks if an adjustable limit switch is feasible			I	T	1				B	A
		D2: he proposes to manage the door opening angles with it in order to apply the same door on different baths			S							
		TD-D1: they joke on the standardization of designer's proposals	Ironic tone	TD: he stands up and observes the pivot (projected at a big size on the screen) from a closest viewpoint. He remains silent and moves towards a corner to be alone				4	3			
		ALL: they suggest a series of solutions for the door regulation	Confused tone and voices overlapping		D	T	4		2			A
		TD: he concludes by assigning few task to TE for the project development. He asks TE to create a precise view of the old product		TE: he opens, rotates and zooms the model as required TE: he extracts the required dimensions	S I		1	5				

Figure 4. Example of Interaction Analysis: verbal transcriptions and metrics values fulfillment in the case of the re-styling of a company's successful product line.

5.3 Results

The distribution of the *stages of collaborative cycle*, the relevance of the various *design contexts* and the use of the different *interaction and communication styles* are assessed by analyzing the time spent for each flow of action characterized by the corresponding metric and by measuring their occurrences. Table 3 presents the average data related to the experiments carried out both in virtual and traditional set-ups. It has been rounded down the total average values.

The pilot study has shown that the VR-based and traditional DR environments produced different outcomes in terms of participants' behaviors and cognitive actions

The analysis of *the stages of the collaborative cycle* distribution highlights that time spent for discussion in the virtual environment is lower than in the traditional one (16% instead of 35%). Although VR representations are realistic and impressive, they do not really stimulate brainstorming, amending, proposing, etc., that represent co-elaboration activities. This can be due to the fact that sessions' participants are mainly focused on the media of interaction instead of the object's task. It is also pointed out by the pointing gestures metric: in VR is 1 while in the traditional set-up is 2.

Analyzing the recorded data, we have observed that in the virtual environment the inquiring stage is characterized by questions related to the use of the adopted technology and on how to carry out specific actions on the virtual prototypes. On the contrary, in the traditional set-up users generally ask for reasons about design decisions and for modifications in shape, functions, etc.

Table 3. Average value of some metrics calculated for the analyzed design review sessions

CATEGORIES	METRICS	TIME (MIN) IN VR SET-UP	TIME (MIN) IN TRADITIONAL SET-UP
STAGES OF THE COLLABORATIVE CYCLE	Presenting	22	29
	Inquiring	20	15
	Discussion	14	36
	Solving	29	22
	Total	85	102
DESIGN CONTEXT	Ergonomics	8	4
	Market	5	6
	Technical	55	51
	Aesthetic	12	15
	Total	80	76
CATEGORIES	**METRICS**	**OCCURRENCES IN VR SET-UP**	**OCCURRENCES IN TRADITIONAL SET-UP**
INTERACTION STYLE	Referring to the model	13	6
	Interacting with the model	11	18
	Simulating action	3	6
	Adopting different viewpoints	4	9
	Total	31	39
COMMUNICATION STYLE	Simple speech	5	12
	Highly descriptive language	25	7
	Pointing gestures	1	2
	Representational gestures	8	0
	Writing, annotating, marking-up	7	2
	Free-hand sketching and diagramming	5	3
	Total	51	26

From this preliminary results, we can deduce that the VR technology should be improved in terms of usability and interactivity in order to reduce users inattention and to improve the concentration on tasks goals.
Concerning the *Design Contexts*, we have observed that in the virtual environment the time spent for evaluating ergonomics is double the value in the traditional set-up. This is due to the fact that the adopted technology does not support physical ergonomics analysis and users need the physical prototype to assess the size of the product, the accessibility of the control buttons, the stresses on joints during the product use, etc. Values for the other design contexts are quite similar. This underlines that the focus of the collaborative session does not depend on the adopted media but only on the design stage at which the review takes place.
Interaction Style analysis shows that the use of product models are quite different in the two modalities. Within the virtual environment, style nr.1 (referring to model) prevails (13/31 vs 6/39) while style nr.2 (interacting with the model) is lower than in the traditional environment (4/31 vs 9/39). This demonstrates that virtual models improve the visual representation of concepts as users choose to refer to the model in order to focus on particular aspects of product design and to attract participants attention. On the other side, users expectations are not completely satisfied as the interaction is poor and the system does not allow evaluating the effect on the 3D model in real time. simulating action in VR is 3/31 while in traditional set-up is double sized.
Furthermore, participants generally place in front of the display and look at each other only in case of discussion about marketing issues. During problem solving they refer to model in order to highlight modifications but human interaction is limited at specific DR contexts. On the contrary, in traditional DRs style nr. 2 (interacting with model) and nr. 4 (adopting different viewpoints) are predominant (respectively 18/39 and 11/39). The adopted VR system provides a very good visual product representation but multimodal interaction is not carried out due to the lack of touch. Virtuality affects perception and following cognitive actions.
Communication Style analysis highlights that each communication channel is well exploited within the virtual environment, even if a descriptive language usually prevails on the emotional one. Within VR set-up, descriptive language (25/51) is often associated with representational gestures (8/51) and participants often move close to the display, gaze at the image from a closer viewpoint and even touch the projected surface. It could mean that users need creating a tangible relationship with the referred

model but interaction is not allowed by the adopted technology. On the contrary, traditional DRs stimulate emotional response and simple speech (5/51) as perceptual stimuli are mainly impressed. Gesturing usually consists on touching physical prototypes and graphic communication is based on paper sketches.

The level of *Mutual Engagement* provided by VR is definitely low and need to be improved. Activities nr. 2 (turnover of ideas) and 4 (attunement between participants) are quite supported (respectively 10/22 and 9/22) but not the others. In particular, physical orientation is completely absent in the virtual modality while it widely contributes to create a shared interaction space and a common involvement within the traditional context (12/28). VR system generates a sort of engagement but it remains at an individual level while need to became a mutual feeling. Analysis of *Cognitive Design Actions* can be described following the three aspects we propose. About *Modeling*, no real-time changes usually take place during DRs so ideas are mostly generated before or after modeling. We think that it depends on users skills in CAD modeling as among conceptual design collaboration participants there are not CAD operators. However, an easy-to-use modeling toolkit could stimulate self modeling. *Perceptual actions* are more frequent in the virtual context than in the traditional one. Moreover they have been changed in type and characteristics. In virtual DRs, attention to relations (B) prevails (9/14) while in traditional DRs attention is focused on elements' collocation (C) (10/18). Also *Set-up goals actions* are more numerous in the VR-based (10/14) than in the traditional set-up (4/18). Both new emerging ideas (A) and past experience reuse (B) increase. This depends on complexity of product representations and on the multiplicity of design alternatives evaluated in real time. This allows rapidly assess technical feasibility without additional meetings.

Statistical analysis has not yet been carried out as the protocol analysis has been applied to a limited number of DRs (4). Hence, the collected data are not enough for deducing meaningful results. However some interesting considerations can be inferred to compare virtual and traditional set-ups:

- Differences in users behaviors and interaction style depend on individual skills and on the level of abstraction supported by the adopted representational means. Foam models stimulate users to focus on technical details and ergonomic issues while the virtual ones well support abstraction and problem-solving at the team dimension. VR best fits conceptual design collaboration in terms of perceptual and set-up goal actions;
- Mutual engagement is poorly supported due to the lack of product models physicality. This is also outlined by changes in the communication style. It is mainly characterized by pantomimes, metaphors, a more descriptive speaking, visual narrations, actions simulation, body and hand gestures;
- Interactions with models are not supported. Users cannot tangibly perceive surface finishing and differences in materials as the sense of touch is not simulated. Moreover, different viewpoints cannot be shared in the same product space. Despite the use of an optical tracking system, a single user interaction is only allowed. The other participants are only viewers and not actors in the discussion while referring to the virtual model space.

6 CONCLUSIONS AND FUTURE WORK

The present paper aims at investigating how to create innovative spaces for supporting industrial design collaboration by defining a protocol analysis to monitor teamwork collaboration in different testing environments, supporting face-to-face meetings.

Main novelties in the proposed approach regard with the definition of a cognitive model to interpret design review sessions, the goal of the analysis, the defined protocol with measurable metrics able to outline interactions between users and digital media focusing on users cognitive actions instead of systems usability, and finally with the structuring of different observation techniques to capture users at work.

The application of the proposed protocol allows the assessment of the impact of physical and virtual prototyping on collaboration. Results are particularly meaningful in order to address advances in human-computer interaction at the teamwork dimension. Volumetric visualization by electro-holographic displays may be able to support all interaction styles. As demonstrated by interaction analysis they can be also improved by adopting hand gestures interfaces to refer to models in a natural manner. In parallel, results highlight the need to simulate physical effects by which materials can be brought into a state in which certain physical properties and behaviors can be emulated.

Future work will be focused on a wide collection of data comparing not only physical and virtual prototyping but also different virtual environments based on Mixed and Augmented Reality, Tangible Virtuality, etc. In particular we are interested in assessing different sensorial conditions by adopting combinations of VR-based interfaces. Furthermore, the proposed protocol could be enriched by comprehending more concepts from cognitive design theory and NLP foundations in order to better investigate human interaction. Finally, additional work should be focus on investigating the reliability of the coding and detailing the proposed metrics.

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