Blended Spaces for Integrated Creativity and Play in Design and Engineering Processes

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The umpire whispers: "Please Play." We sort of play. But it is all hypothetical, somehow. Even the "we" is theory: I never get quite to see the distant opponent, for all the apparatus of the game (Wallace, 2011, Infinite Jest, Hachette, UK). We find no reason to abandon the notion of play as a distinct and highly important factor in the world's life and doings. All play means something. If we call the active principle that makes up the essence of play, "instinct," we explain nothing; if we call it "mind" or "will" we say too much. However, we may regard it, the very fact that play has a meaning implies a nonmaterialistic quality in the nature of the thing itself (Huizinga, 2014, Homo Ludens, Ils 86, Routledge, London.). This paper builds on the notion of integration of creativity and play in design and engineering environments. We show results of ongoing research and experimentation with cyber-physical systems (CPS) and multimodal interactions. The use of computational tools for creative processing and idea generation in design and engineering are mostly based on commonly available 2D or 3D CAD programs, applications, and systems. Computer-generated creativity is mostly based on combinatorial power and computational algorithms of the intrinsic system duly orchestrated by the user to manifest outcomes on a variety of processes. However, integrated game-based CPS ecosystems could enhance the uptake of play, imagination, and externalization within the design and engineering process. [DOI: 10.1115/1.4033217]

Introduction

The computer was made in the image of the human [1]. Technological constraints are a given challenge and working within them always fosters creativity. Ideation (i.e., design and creativity) is still done with traditional analog manual tools and is used next or parallel to current computational tools.

Our tools dictate the nature of our work. Often software interfaces define the boundaries of our work, but only exploration into the margins of these tools, beyond the intended use pattern, can really expose these boundaries. In that sense, in order for us to break out of the design paradigm embedded in software, we must use it "the wrong way" [2].

The research on hybrid design tool environments (HDTEs) for design and creativity tries to provide a simple, effective, flexible, and efficient workflow and still not limit the creative output and ideation processing. In combination with game-based CPS ecosystems (e.g., hybrid design spaces and CAD games), the creative human capabilities (inspiration and imagination) and capacity to playfully collaborate or work alone in design and engineering processing coincide with the intuitive natural human ability to interact, communicate, and challenge conventional thinking [3].

In this paper, we present emerging scenarios and report on possible transformative approach in interaction, devices, usability, design tools, and design spaces. Furthermore, we show the results of ongoing experimentation and testing of HDTEs.

Humans, Machines, Systems, and Interaction

Humans, machines, and systems are incorporated, embedded, and take fully part in all areas, sectors, territories, and domains of our 24/7 economy to fulfill, assist, or support our daily tasks, work, communication patterns, and lives. Everything seems connected or is connected by some sort of means, service, or proxy. Consequently, we immerse ourselves in analog and digital realms seemingly effortless, constantly meandering between real and virtual environments. There is hardly an escape or possible denial of the digital revolution in our daily routines from technologically communicated, facilitated, and/or (hyper)mediated interactions.

Although computers are encroaching into territory that used to be occupied by people alone, such as advanced pattern recognition and complex communication, for now humans still hold the high ground in each of these areas [4]. People can excel in interactions and communication with others and possess amazing capabilities to use these complex skills to gather information or have an influence on others behavior. However, computers and systems are getting better and better in doing virtually the same complex set of sensorial "understanding" and recognition of recurring motives.

Virtual assistants are quite common practice these days (i.e., services, communication, and information) and are often more cost-effective and efficient in their repetitive task fulfillment and core functionalities. Humans continue to have, at least for the time being, an advantage in the physical domain in which they use their abilities and capabilities in often advanced and complex situations in either physical or cognitive challenges (i.e., communication, psychology, and cognition). In general, people are great problem solvers in the physical and metacognitive processes, often ambiguous, nonlinear, uncertainty, predictable, or unpredictable but always in the state of motion, intent, and interaction. Putnam [5] points out that any adequate account of meaning and rationality must give a central place to embodied and imaginative

Subjective	—	Objective
Mind	—	Body
Liberal Arts	—	Natural Science
Human / Person	—	User / Customer
Internal	—	External
Implicit	—	Explicit
Virtual	—	Physical
Experiential	—	Practical
Human-Experiential Design	—	User-Experience Design

Fig. 1 Transcending structures of bodily experiences

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structures of understanding by which we grasp our world. The structure of rationality is regarded as transcending structures of bodily experiences (Fig. 1).

Human reality and experiences are shaped by the patterns of our bodily movements, the contours of our spatial and temporal orientation, and the forms of our interaction with objects. It is never merely a matter of abstract conceptualization and propositional judgments [6].

Our hypothesis is that embodied imagination (i.e., physical experiences and its structures), intentionality, and metacognition could simultaneously "link" these physical and mental faculties (individually or collaborative) congruously with the digital realm based on our natural physical and intuitive interactions and explorations. The deep meaning of embodied cognition is that it enables disembodied thought [7]. The key question here is: Are embodied representations, our expressions developed from our bodily perceptions and imaginative systems of understanding adequately shared to be thought of as appropriate to knowledge? Or are they too subjective, unstructured, and unconstrained? To paraphrase Johnson, ".there is alleged to be no way to demonstrate the universal (shared) character of any representation of imagination" [6]. There seems to be an undeniable oscillation between objectivism and subjectivism that could lead to relativism. According to Schön [8], it seems right to say that our knowing is in our action and interaction. In the fuzzy front end of creative processes, ideas are often visualized in one's imagination and externalized through 2D and/or 3D representations. Rationalizing these ideas using "supportive machines" (virtual assistants) is of primary concern for rawshaping technology research. Instead of externalizing only the final results of a creative process, recording the separate iterative steps of the process can help in rationalizing the thought process. Furthermore, an overview of the previously created representations can lead to new insights and richer ideas, whether these representations are physical or virtual (Fig. 2).

Brereton [9] describes four dimensions along which representations can be classified (Fig. 2). We concur with Johnson [6] that imagination is recognized to play a role in the "context of discovery," wherein we imaginatively and iteratively generate new ideas, concepts, and connections; but it is excluded from the "context of justification" which is restricted solely to the tracing of logical connections (objectivism).

Linking both analog and virtual worlds, as shown in Fig. 1, was already present during the initial wake of the computer revolution; the idea of "disembodied cognition" became very popular [10,11]. The trouble here is that being "disembodied" created great challenges, frustrations, and problems to solve in human interaction with machines. Virtually everyone agrees that human experience and meaning depends in some way upon the body, for it is our contact with the entire spatiotemporal world that surrounds us [12]. Embodied understanding is a key notion; we are never separated from our bodies and from forces and energies acting upon us to give rise to our understanding (our "being-in-the-world"). So, this "being-in-touch-with reality" is basically all the realism we need. This realism consists in our perceptions and sensorial understanding that makes us feel, touch, explore, and come-to-grips

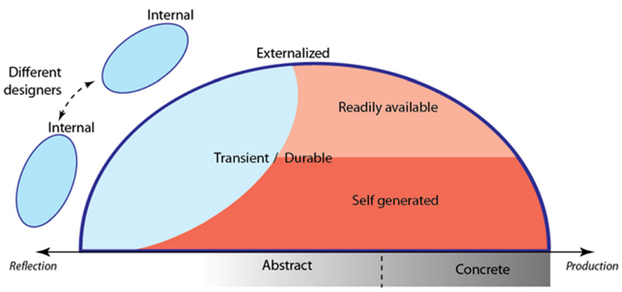

Fig. 2 The four dimensions along which representations can be classified in design processing

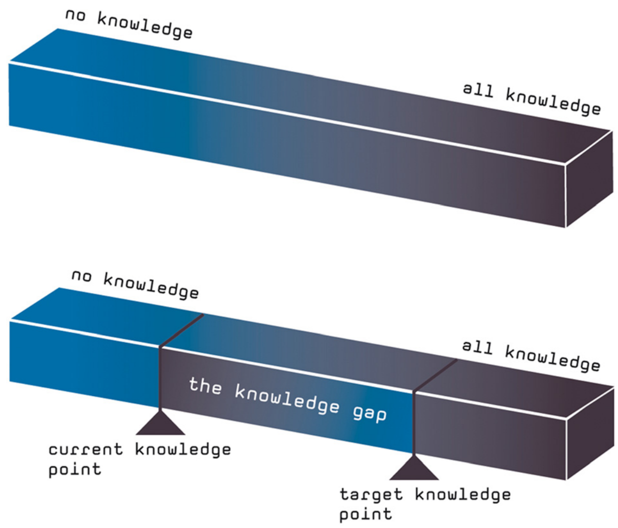

Fig. 3 The knowledge gap in human–computer interface design

with reality in our bodily actions in the world. Moreover, we need to have an understanding of reality ample enough to afford us to fulfill a purpose or task nearly successfully in that "real" world. Polanyi describes the human body as an instrument, the only instrument that we normally never experience as an object. Because we experience our body in terms of the world to which we are attending from our body "…we feel it to be our body, and not a thing outside" [13].

Blindfolded, Tangibility, Tacit, and Haptics

Direct demonstrations of embodied and disembodied views of conceptual representation are shown in the following experiment we conducted. The aim of the experiment is to measure, observe, and quantify tacit and tangible knowledge through haptic

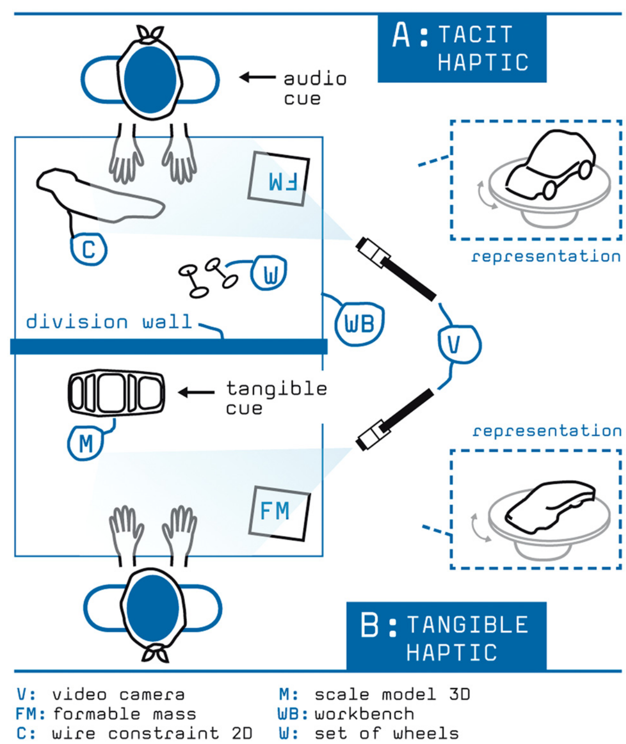

Fig. 4 Setup blindfold conceptual processing

Experimentation Blindfolded Representation	A	B
	tacit haptic	tangible haptic
number of participants	79	79
total high speed video test time edited (mm:ss)	43:00	43:00
real total video test time (h:mm:ss)	7:13:00	7:04:00
average test time per participant (mm:ss)	05:29	05:22

Fig. 5 Multimodal user interaction during blindfold experiment

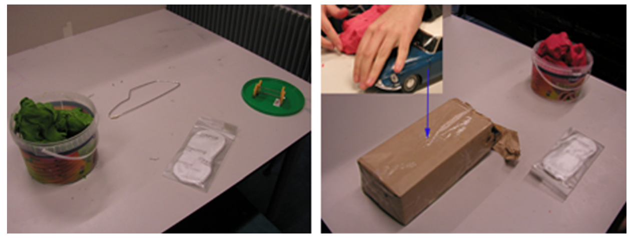

Fig. 6 Setup tacit (L) and tangible (R) cues

Fig. 7 Tacit haptic (L) and tangible haptic (R) representation

representation without visual clues. Polanyi [13] stated the fact, by reconsidering human knowledge, that we can know more than we can tell. When we touch something with our hands or with a tool, our awareness of the impact is transformed into a sense of what thing or object we are exploring. An interpretative effort transposes meaningless feelings into meaningful ones [14]. According to Collins [15], this is the semantic aspect of tacit knowing. In this experimental setup, we will need to both assume a relatively low prior knowledge of the user and aim to reduce the required knowledge to complete a given task as well. As such, we need to take a look at the lowest common denominator in terms of prior knowledge and the required level of knowledge a user needs to have to complete a given task with our interface. The gap between the knowledge a user already has and the knowledge a user requires to complete a given task is our research focus in intuitive interfaces, multimodal processing, and HDTs (Fig. 3). According to Spool, if there is indeed a gap in knowledge levels, an intuitive design will be a design that will help the user bridge this gap subconsciously [16]. In order to achieve this, we draw on associations and metaphors that common users are already familiar with in real life. At the same time, we acknowledge and recognize the aspects of uncontrollable bias, uncertainty, approximation, and unpredictability in real and synthetic environments [14]. The participants, 158 university bachelor students (male and female) from Industrial Design Engineering, were all blindfolded during the execution of the conceptual processing tests (Figs. 4 and 5).

Blindfolded participants were given either aural instructions or tangible instructions in recreating an automotive artifact (idiosyncratic design icon). Seventy-nine participants were given an audio cue (disembodied), a wire size constraint, and a set of wheels (Fig. 6—left). The set of wheels were for the users to fix to the clay model in order to see if they had a certain sense of spatial temporality to position them more or less correctly in their tangible model. The other 79 participants got a scale model (embodied) of the iconic car (boxed) (Fig. 6—right). The user task was to make a tangible representation in either green clay (tacit–haptic) or red clay (tangible–haptic) with a time limit of 5 min (Fig. 5). By using solely haptic perception, in one case aided by aural instructions, the participants had to identify, recognize, recreate, mimic, and make a 3D representation of the shape (Fig. 7—left and right). End results from tacit–haptic interaction (green models) and tangible–haptic processing (red models) showed great differences in shape and form, quality, structure, configuration, and representation (Fig. 8). The experimentation showed that haptically sculpting with a tactile role-model gave a greater precision, mimic, and resemblance to shape and form in contrast with users that solely relied on aural and tacit input. The results show interestingly the differences in both approaches and approximations, thereby illustrating the apparent dominance of using the senses of touch and proprioception. However, this is *not* to state, point out, and/or argue that the green models are of "less" interest, little value, or quality. On the contrary, both sets of end results show

Fig. 8 End results of tacit and haptic processing

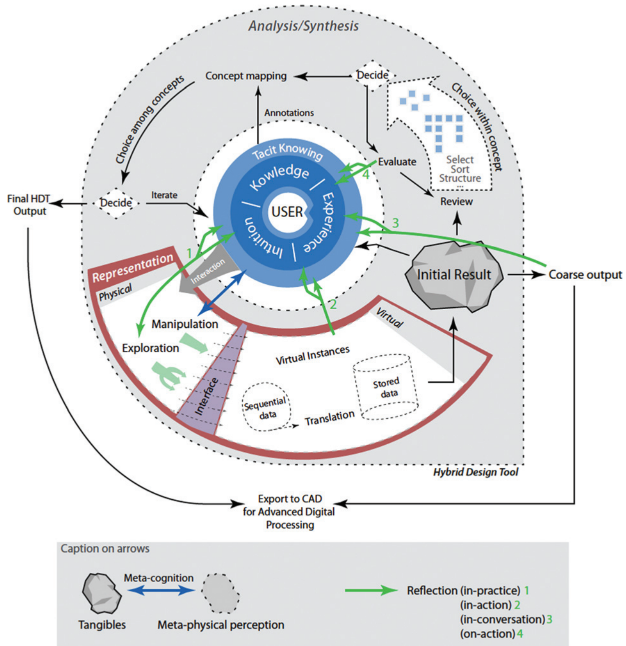

Fig. 9 HDTE—user-centered design process flow diagram

the meaning and difference in use of sensorial and metacognitive representation and externalization.

Furthermore, the absence of visual input during the design process results in an explorative nature (metacognition) of the process. The importance of tangible feedback becomes apparent for the understanding of shape and intuition in representation. Although visual input is extremely important in a design process, tangible feedback forms a substantial part of understanding shape and cannot be neglected as input for design tools [17]. For more in depth studies, we refer to our primary research and data [12,14,17–23].

Blended Spaces and Tools

Reflection, incubation, and learning are encouraged when technology is supportive and calm; it allows user-control, engagement, and foster learning skills while harnessing talent [14]. A lot of research is being directed in the past/present toward human–computer interaction (HCI), exploring the functional cognitive seams, and will continue so into the future.

McCullough [24] calls this “human–computer partnerships” that will be developed to make the interaction more superfluous and natural feeling. Many argue that it is not really necessary to mimic the real phenomena in the virtual or to create sameness in experience and representation within synthetic worlds. This is partly true for maybe some virtual areas, like, for instance, gaming as entertainment or playing in virtual realms. When it comes to creativity, serious gaming, design, manufacturing, and engineering, the need for real-world reflection, recognition, and mimesis is often a prerequisite for successful simulated experiences, processes, and interactions. Knowledge development and acquisition is a resource in the constructions and representations.

A wide variety of tangible and virtual models are constructed and used to support the processing and communication. According to Sellen and Harper [21], studies with computer-supported collaborative workspaces have shown that artifacts such as “pencil and paper” play a critical role in supporting social interaction and collaboration. For designers, paper-based sketches and low-resolution modeling have also shown coordinative advantages [22].

In the HDTE, the user is central in the design processing and interaction multimodalities. The experience of the HDTE aims to achieve a richer and more serendipitous design and engineering process that include the integration of distributed cognition, experiential learning, and augmented representation during conceptualization and ideation. Figure 9 shows a HDTE and a suggested flow diagram indicating the design processing whereby the user(s) is rendered central.

The blue arrow represents the metacognitive interaction between tangibles and the metaphysical perception of the user. The green arrows represent different types of reflection that can occur during the process. Findings and preliminary conclusions on various modalities (e.g., analog, digital, and hybrid) in tool use, interaction, and processing showed remarkable correlations and differences between user knowledge, experience, expectation, performance, and motivation, as shown in Table 1.

Notably, in the early design and engineering phase, the role of tools is noteworthy, especially in terms of what kind of tools to choose, decisions have to be made about what kind of process to use and how. Furthermore, every choice and decision has its direct, explicit, and implicit implications on the individual task, outcome, and process as a whole. A hybrid tool can provide a continuous challenge between the visual and tangible representation (Fig. 10). New users learn to use the tool through exploration and experimentation.

Virtual tools offer advantages like, e.g., sharing information, metadata, visual representations, and simulation. However, due to high learning curves, the design process with these tools is rigid, nonintuitive, and limited in stimulating creativity. Gameplay, on the other hand, tends to be regarded as memorable and formative experiences. Intuitive, imaginative, and stimulative are attributes that spur natural creativity. If games are profoundly imbued for purposeful play, thriving on tacit and explicit knowledge of the user, a CAD system carefully stylized with ludic mechanisms could potentially be highly productive [3]. In most CAD systems, the designers are required to change their skill sets to meet the

Table 1 Online user survey and feedback

	Results		
Questions	Analogue	Digital	Hybrid
Previous experience with design tool?	100% yes	85% yes	7% yes
What is your experience with design tool?	Intermediate	Intermediate	Intermediate
The tool was easy to use?	Agree	Disagree	Agree
The tool facilitates easy recovery?	Neutral		Neutral
The tool supports fast productivity?	Agree	Neutral	Agree
Overall satisfaction with tool	Strongly agree	Disagree	Agree
Design task performance is fluent and direct?	Agree	Sometimes	Always
How does the tool meet you expectations?	Very good	Mediocre	Good
My creative output was successful?	Minor problem	Problem	No problem
The interface of tool is pleasant?	—	Agree	Agree
Exploring software features by trial and error?	—	Hard	Easy

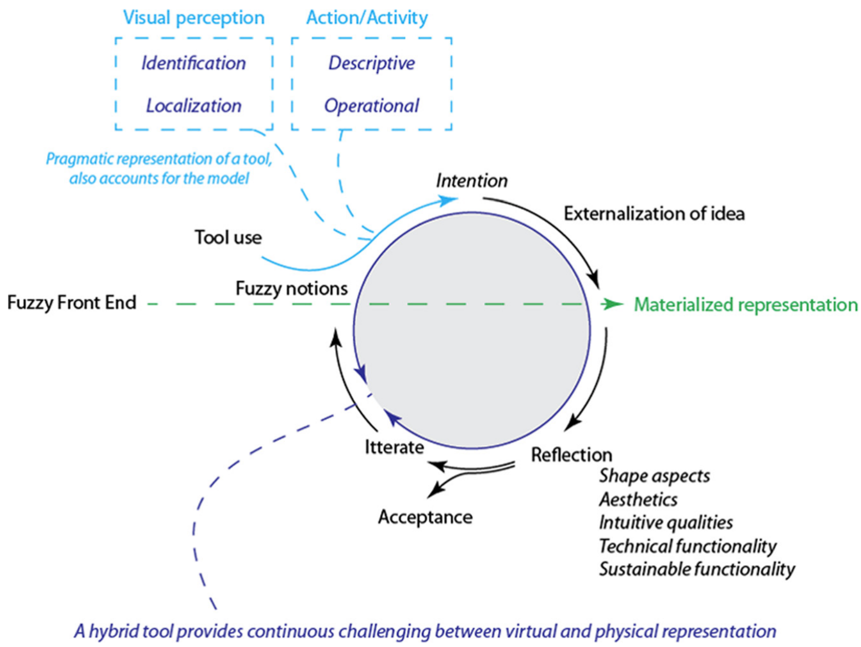

Fig. 10 HDTE—continuous challenge between real and virtual representation

demands of the interface, instead of changing the interface and functionality to their demands.

Pairwise Comparison of HDTE Tools

A pairwise comparison interaction experiment with two HDTs (i.e., LFDS and NXt-LFDS) [12,14,18] are executed to generate user interaction (UI) and user experience (UX) data required for the analysis and evaluation (Fig. 11). Both tools are set up together for the benchmark test (Fig. 12). A total of 15 participants ($n = 15$) were asked to perform a design task with one of the HDTs. All participants were university bachelor students from Industrial Design Engineering. We tested eight students (five males and three females) on the NXT-LFDS and seven participants (five males and two females) on the LFDS. We placed one participant per HDT, executing the design task simultaneously so they could have a more engaged experience. After approximately 12–15 min, they changed machines. Total interaction time is 25–30 min; we anticipate that the users (user groups) can provide more profound feedback on the usage and interaction.

The design task was to ideate and conceptualize a hydrogen car from scratch. The aim is to get as much iteration as possible within the specified time (also known as iteration galore) [12]. Some 3D AM tangible artifacts (i.e., wheels, motor, and hydrogen fuel cells) were supplied to act as metaphorical constraints (Fig. 13). Furthermore, they had access to traditional design tools, paper, constructing materials, and so forth.

The collection of data consists of three main methods as follows:

- observations—of both facilitator and by video analysis
- online survey—user feedback on several IA issues
- user results—process, speed, iterations, and user created content

We extract the data on usage, interaction, and relations between input and output. The acquired data will be evaluated and analyzed in order to provide the foundation for writing the recommendations and further development of the ongoing research on HDTEs [14,25–27].

The participants received a short introduction on the working of the HDTs before they started the design task. However, most of the participants still asked for help with certain functions that seemed intuitive at first. Most users first showed some caution in trying different features and exploring possibilities. The 3D sensorial space of the HDTs was not clear to almost all of the participants. They could not grasp this simple "trick" of spatial perspective-taking and most started their iterations in 2D (flat) representations. They placed the objects and constraints on the workbench thereby not using the capability of 3D sensorial space to take a perspective snapshot of an object.

After a simple "nudge" (facilitator) in the direction of the illusion of perspective, some participants got the idea. Some needed a simple demonstration to understand the perspective visualization. Others needed just the words "3D" and "perspective" to make the connection. Nevertheless, all participants, except one, needed this nudge. This gives an indication about the intuitive interface and blind spots of/in user interaction and processing.

Fig. 11 Various LFDS configurations and embodiments

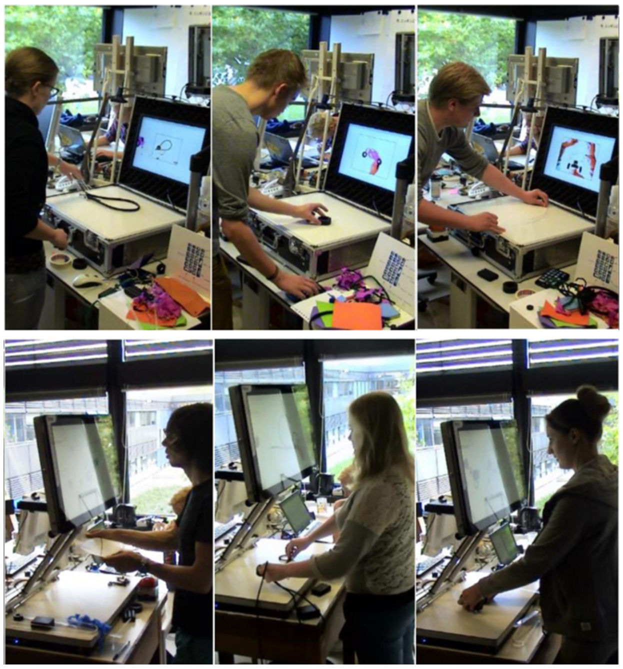

Fig. 12 Pairwise comparison of HDTE tools: LFDS (top) and NXt-LFDS (bottom)

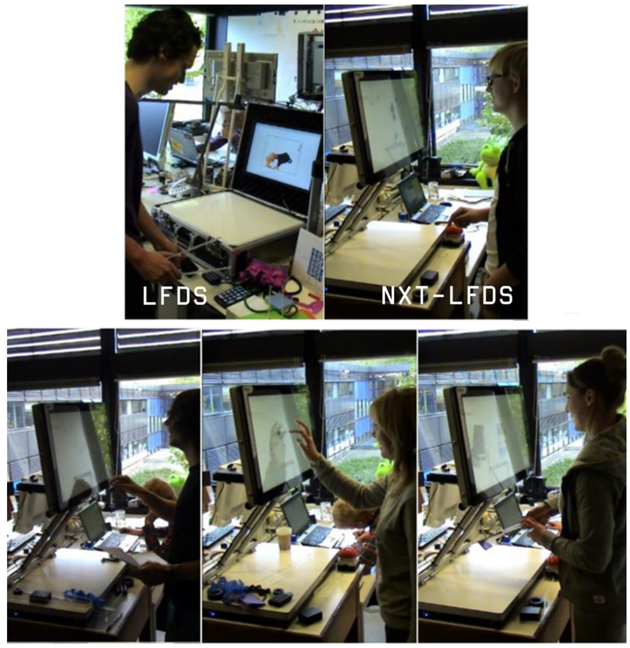

Fig. 14 LFDS versus NXt-LFDS engagement and enjoyment

The overall performance to create 3D iterations in perspective and make real-time captures seemed difficult. Participants were observed (i.e., facilitator and video recording) and seemed to struggle holding artifacts and/or objects in the right position to make iterations. To place a physical object in 3D perspective position is difficult and requires full body control, intrinsic skill sets, manual dexterity, hands–eyes coordination, and strong visual-perspective prowess. Patience and relaxation is required to position objects in 3D space.

Some of the users clearly showed signs of frustration and lacked patience, experience, and motivation to fulfill the task successfully. This has direct implications on the generated iterative content, quality, performance, and direction of the iterative solutions.

Finally, the NXt-LFDS monitor was more directly present for the participants due the embodiment design and architecture of the machine (Fig. 14). The interaction with the NXt-LFDS takes place in the 3D sensorial space underneath the monitor, compared to the LFDS; there is a sort of blind spot where the users' hands are manipulating the artifacts and objects. The monitor physically obscures part of the interaction; therefore, watching the monitor and virtual visualization becomes more prominent during interaction.

We observed engagement and motivation during the experiment; however, some participants did not quite follow the task and created "art" instead. If asked whether they would drive in such a car, they responded with "no." The questionnaire revealed that they saw the tool more as a fun thing to play with, instead of using it to create conceptual solutions for real design problems. However, after users got the "hang of it" (experiential), they started to become more and more creative in their iterations and use of the provided constraints and reflective materials (Fig. 15). Most showed signs of enjoyment and pleasure. This is shown in the total of iterations made, the variety and diversity in iterative content through translation and transformation of the 3D materials and objects. The figures clearly show the randomly selected results of the iterative hybrid design processing.

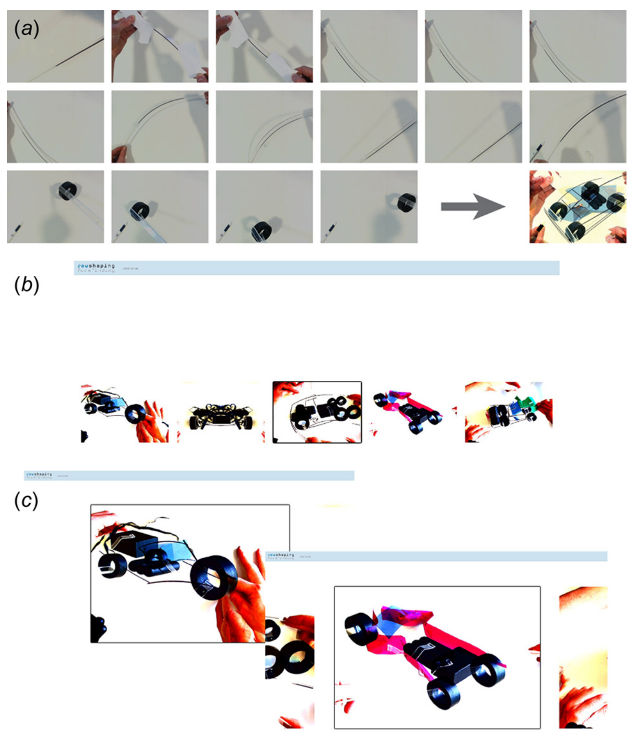

Fig. 15 LFDS and NXt-LFDS iterative virtual processing

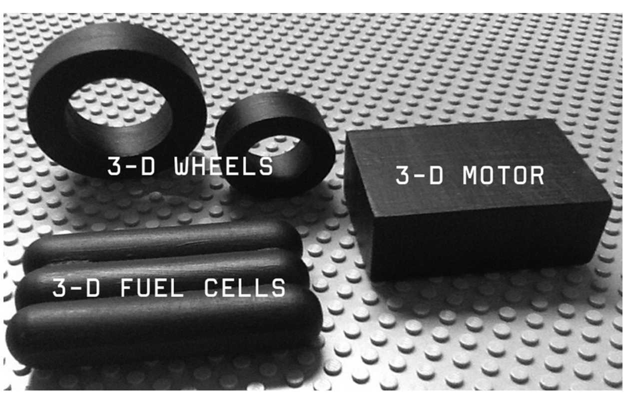

Fig. 13 Three-dimensional AM tangible constraint metaphors

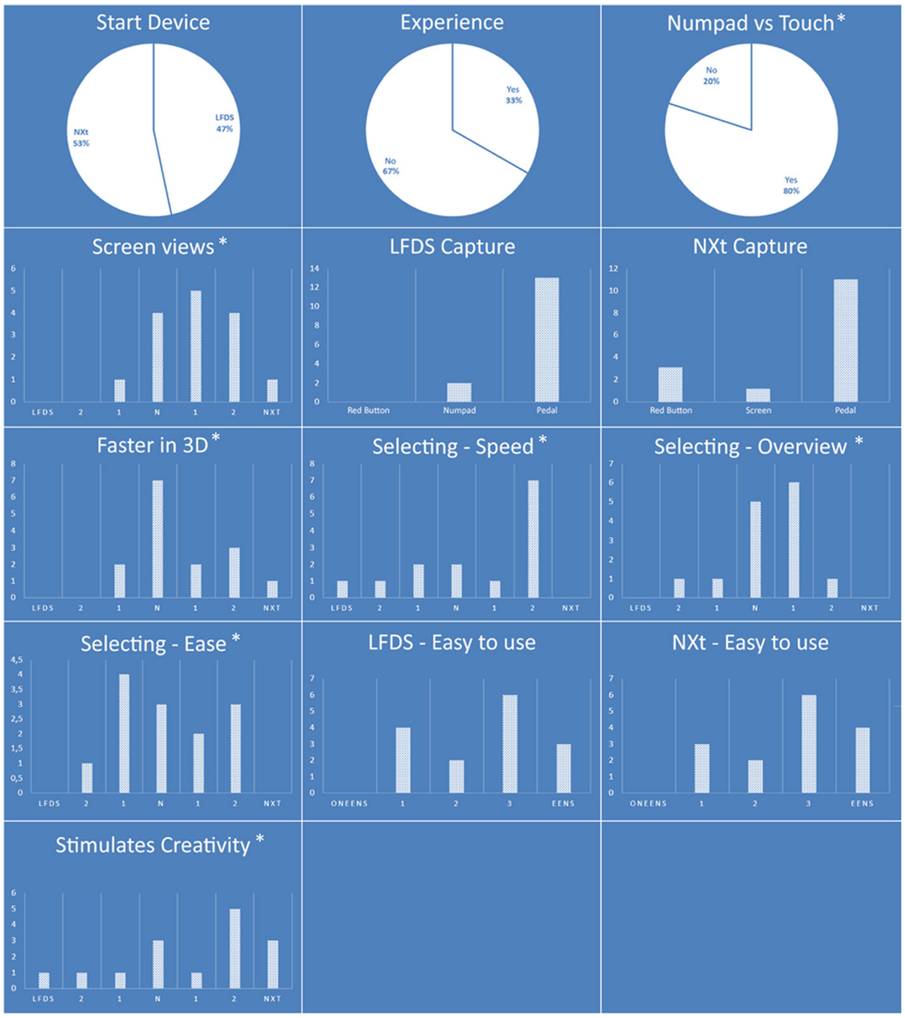

Fig. 16 Pairwise comparison of LFDS and NXt-LFDS

Over time the participants became more familiar with the tools and the interaction and outcome greatly improved. Video analysis and observations showed immersive interaction and signs of flow during processing. We identified concentration on the task at hand, nondistracted processing and focal intention on the interaction with the tools. The tools evoked serendipity in generated content, creativity and stimulated the users to try out effects with different materials (Figs. 15 and 20). A concern was to keep the motivation of some the participants, toward the end initial enthusiasm turned around and slightly faded.

With all the issues and difficulties the participants addressed, one might think that the experiment was not fun at all. On the contrary, all the users did enjoy the testing and found it insightful and enhance their creative and imaginative abilities. The participants gladly and willingly provided feedback and suggestions for improvements. In Fig. 16, we show the pairwise comparison based on the former indicated features and aspects.

In Tables 2 and 3, we present the data that are evaluated and analyzed based on the user performance (i.e., quantity of iterations, speed, and merged iterations), user interface (UI), processing time, and UX (i.e., ease-of-use, usability, and graphical UI (GUI)). Data are taken from the 15 participants (Fig. 17), as shown in Tables 2 and 3; the iteration per minute is 4.11. The amount is slightly higher than previous tests [26]. A total amount of 1108 iterations yield 77 merged results, referred to as

Table 2 Combined HDT's test results in totals

Totals	
Iterations	1108
Excl gr 4	1034
Start	771
End	337
Sketches	77
Time taken	4:29:28
IT/min	4.11

Group	Naam	Start Device	LFDS Iterations	NXt Iterations	LFDS start	LFDS end
1	Jeroen	LFDS	54	21	15:39:08	15:54:13
1	Michiel	NXT	28	32	15:57:21	16:01:26
2	Hilde	LFDS	51	34	12:01:19	12:11:05
2	Myrthe	NXT	21	19	12:16:14	12:21:15
3	Marco	LFDS	61	17	13:03:40	13:18:51
3	Peter	NXT	18	28	13:21:24	13:25:00
4	Pim	NXT	21	53	14:23:05	14:26:30
5	Mustafa	LFDS	47	7	11:02:23	11:15:11
5	Alicia	NXT	20	60	13:55:35	14:00:12
6	Thomas	LFDS	69	28	13:01:55	13:15:43
6	David	NXT	21	49	13:22:52	13:27:49
7	Elleke	LFDS	81	27	14:01:44	14:17:10
7	Klaartje	NXT	24	67	14:23:35	14:27:39
8	Rens	LFDS	50	43	15:07:18	15:20:21
8	Goffe-Jan	NXT	16	41	15:26:29	15:32:25

Fig. 17 User interaction test and iterations chart

Table 3 Data from both HDTs based on first and second round

	LFDS	NXT
Iterations	561	473
Start	413	305
End	148	168
Time	2:07:23	2:08:29
Start	1:35:07	1:31:07
End	0:32:16	0:37:22
Iterations/min	4.40	3.68
Start	4.34	3.35
End	4.59	4.50
Task time	0:09:06	0:09:11
Start	0:13:35	0:13:01
End	0:04:37	0:05:20
Sketches	35	35
Start	25	23
End	10	12

Table 4 Mean differences on first and second round

	Sketch	Tim	Time/sketch
Start mean	3.53	0:13:18	03:46
End mean	1.6	0:04:58	03:07

"Sketches" in tables. On average, each user created 5.13 sketches and used 14.4 iterations for each.

On both HDTs, the second round resulted in higher iterations per minute rate. Only the NXt-LFDS has a remarkable higher it/min rate in contrast to the first round. Likewise, the ratio between total start and end iterations is smaller on the NXt-LFDS compared to the LFDS, that is, 1.8 for NXt-LFDS and 2.8 for LFDS. Furthermore, the mean difference between start and end, with respect to time per sketch, is displayed in Table 4. It shows a clear reduction of time needed per sketch on the second round. In Fig. 18, the findings and results are visualized in charts to show the data acquired per group. The iterations per person on both the LFDS and NXt-LFDS are shown in charts A and B. It clearly shows the lower average iterations when users started on the NXt-LFDS. Also, the means of starting and ending are much closer to each other compared to the LFDS. Remarkably, with the first three groups performing on the NXt-LFDS, the iterations lay even closer to each other. Explanations of charts A and B (Fig. 18) are as follows:

Chart A: The iterations per user created on the LFDS. The first user of each group started on the LFDS.

Chart B: The iterations per user created on the NXt-LFDS. The second user of each group started on the NXt-LFDS.

Furthermore, the amount of merged iteration results on both machines is within the same spectrum and shares the same average according to chart C. Explanations of charts C and D (Fig. 19) are as follows:

Chart C: The merged results per device for each group member.

Chart D: The results from the participants on iterations per minute.

The zigzag pattern shows the difference in time users had on their respective rounds. The first round lasted on average 13 min 18 s and the second round 4 min 58 s, for reference see Table 4. The iterations per minute for all users are displayed in chart D. Noticeable are the large discrepancies per user. For example, the highest is 12.73 compared to the lower of merely 2.

User Interaction and UX With HDTE

The NXt-LFDS proved to be a genuine HDT merging analog manipulation in combination with digital virtual representation. Most users showed engagement while performing their interactions; they were motivated and concentrated during the processing. The number of generated iterations and possible solutions (Fig. 20) that were externalized suggests the rationale behind these findings (Fig. 21). Still, a number of issues could break this "immersive state," or flow, due to apparent user frustration and uncertainty in interaction modalities. Most of these issues on the NXt-LFDS are UI related.

The UI of a design tool is one of the most important aspects of such a tool, because of the direct representation and visualization implications of the digitized virtual content. It is the proscenium onto an individual or social virtual reality [12,17,24]. If designed perfectly, the user will feel no drawback or break the "flow" [28]. The interface should therefore be operated on intuition (fuzzy mode) and not predominantly on logic (logic Mode).

From the survey we conducted, it became clear that the users rated the NXt-LFDS higher than the LFDS. The users experienced the NXt-LFDS to be an improvement of the earlier HDT.

Although the users felt that the NXt-LFDS was an improved design tool over the LFDS, the performance of the former was not exceeding its predecessor. Most of the issues can be translated to the graphical design of the UI. The NXt-LFDS uses a multi-touch monitor; the visual appearance seems more cluttered with next to the iterative content showing also the interactive buttons/features. Nevertheless, most of the users found the on-screen interaction more pleasant. The reason being that the focus and your concentration is often solely on the monitor, instead of having to revert back to the numpad (LFDS) for interaction. Still, the interaction proved to be counterintuitive in some functions/

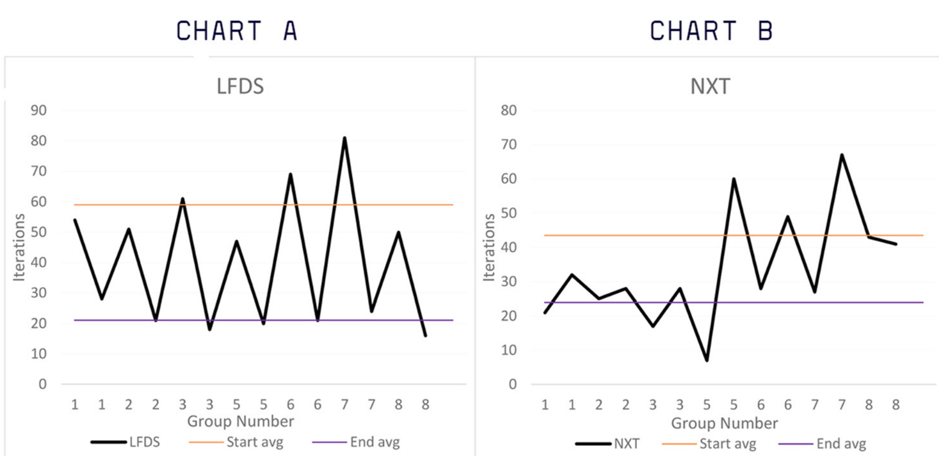

Fig. 18 Iterations/person on LFDS versus NXt-LFDS

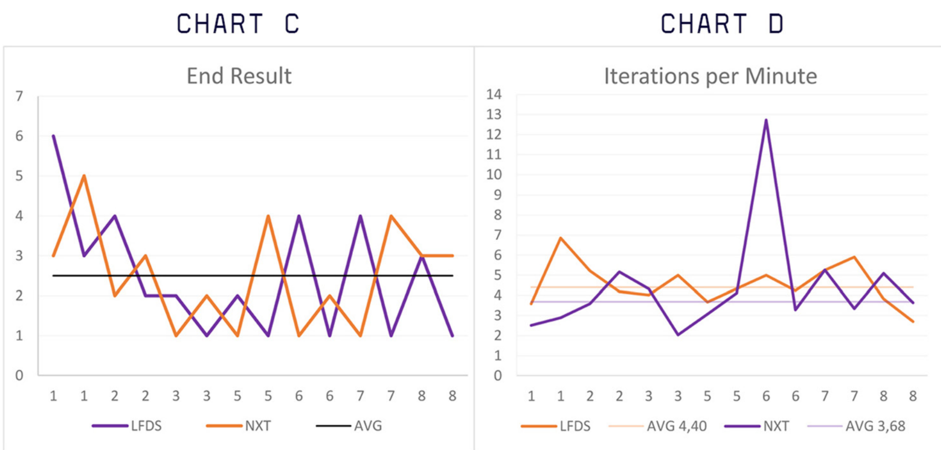

Fig. 19 Merged end results and iterations/minute on LFDS and NXt-LFDS

features. The numpad [18,19], for instance, has each function in proximity of each other and on the GUI of the NXt-LFDS; these functions/features are more integrated and arranged on-screen (Fig. 22). Recommendations for improvement and continual development of the GUI for the NXt-LFDS are necessary to intuit the user interaction and modalities. Furthermore, an important process step in tool-use comes parallel, during or after the "fuzzy front end" (fuzzy mode); the review modality within the so-called logic mode [19] was only used for select and sort of iterations by some participants (Fig. 23). Users, unfortunately, did not really intuitively understand the meaning of the features as implemented in the logic mode (Fig. 24). According to some, the functionality felt sluggish and not fully functional to benefit from. The core of this logic mode needs to be redesigned to fit the vision of intuitive and superfluous interactivity in HCI and HDTs.

Fig. 20 Iterative ideation galore processing

Performance and Expectations HDTE

On both the LFDS and NXt-LFDS, the start-off count of it/min was in general lower than the number of it/min after the switch of machines (second round). A possible explanation could be the initial experience of the users increased their performance and user behavior. One remarkable aspect is the difference in the start and end it/min on the NXt-LFDS. The difference is much larger compared with the LFDS. The lower iterations per minute on the start of the NXT-LFDS could indicate a higher learning curve and possible constraints of the user modalities.

For example, the placement of the touchscreen above the physical–sensorial workspace impairs the vision during interaction with tangibles. The position of the adjustable monitor is therefore important at the start of the design process. None of the participants adjusted or asked for help in repositioning the monitor. This shows how the perceived inherent system qualities are not self-evident and/or self-explanatory for users. Given that the sample rate overall was low, despite the fact that one user made an astonishing amount of + 12 it/min on the second run; the inherent higher value of mean it/min of the second run on NXt-LFDS can be due to this particular outlier.

This could imply that the average will drop if we take this user out of the equation. This will make the difference between LFDS

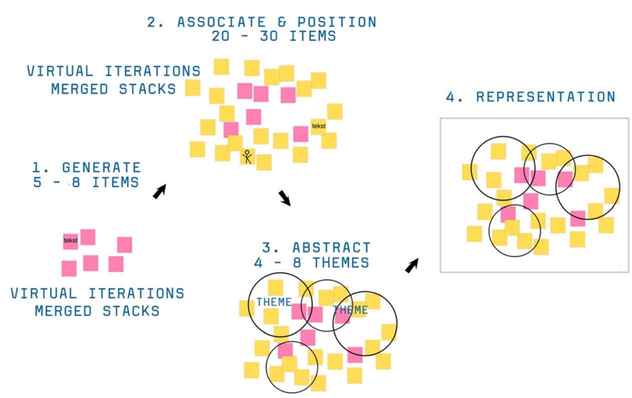

Fig. 21 HDT incremental design processing procedure

Fig. 22 Iterated translations and transformations visualized on processing GUI of NXt-LFDS

and NXt-LFDS even larger and suggest that the LFDS performance is higher and the outcome in iterations per minute is considerably larger.

Furthermore, the average iterations per minute lay higher than in previous experiments. This possibly is due to the fact that the overall interaction and processing time was longer. The users could familiarize themselves with the machines. This in combination with the difference between starting and ending it/min informs us how enhanced UX can play an intrinsic and active role in user performance and task execution.

This phenomenon seems self-evident but does not make transparent the whole issue. To create and design a truly intuitive tool and UI, the difference in performance between an experienced user and a novice user should be minimal, virtually nonexistent. When novice users start to work on the machines they showed signs of uncertain behavior and a tendency to stall the interaction probably out of fear to make mistakes. The cognitive overload in concern of doing something wrong did not invite users to immediately try out the different features and possibilities of the machines. In this case, a well-timed nudge [19] from the machine could trigger the user to start-off the design processing and user interaction.

For example, the machine could display or voice a message: "Place something on the workbench to start." Followed by "Press the capture button (with an arrow directing the attention to the on-screen red button) to capture your work" (Fig. 25). Both machines could inform the user about the multimodalities and tool specifics. If a user places an artifact or object in the sensorial space/workbench and forgets to capture this, the capture button could flash or blink subtle to indicate the user to capture the iteration. The overall performance, experience, and user interaction could be improved by integration of functions, modalities, features, tools, and sensorial actuators to enhance the workflow process.

At the end of the sessions, we noticed a drop in motivation and user performance. Currently, we are analyzing the video footage and evaluate the user comments from our online questionnaires to determine what factors and/or issues led to this lack of interest toward the end of the sessions.

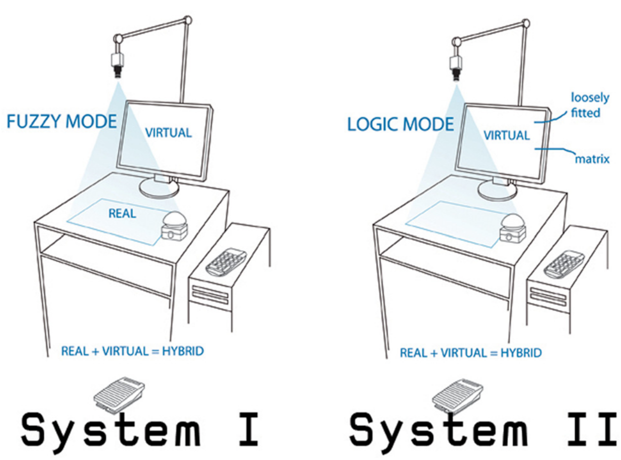

Fig. 23 Diagram of fuzzy mode (FM) and logic mode (LM) to afford multimodal interaction with LFDS-HDTs

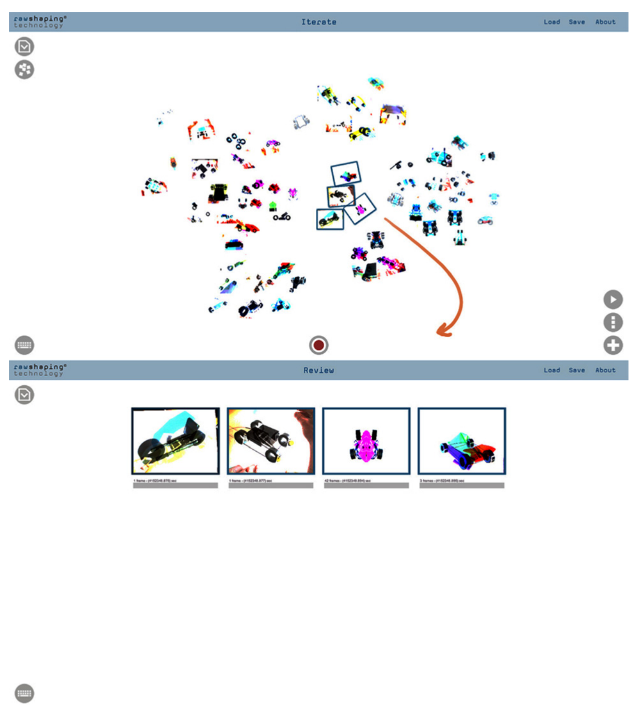

Fig. 24 Choice and decision making of iterations from fuzzy mode (FM) (top) in review pane of logic mode (LM) (bottom) on GUI of NXt-LFDS

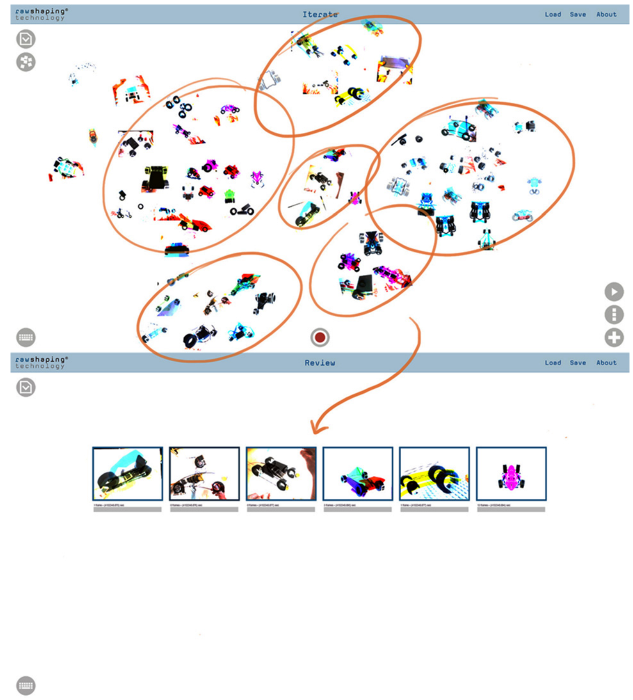

Fig. 25 Final results selection iterations in fuzzy mode (top) and tagged selections (bottom) on GUI of NXt-LFDS

Conclusions

This paper is part of our ongoing research and development of HDTEs; these preliminary findings and results show our variety in approach to tools, tools use, multimodalities, and experimentations carried out to investigate the human-in-the-loop design processing and interaction. Although most users found the NXt-LFDS an improvement in relation to the earlier LFDS, the overall performance of the NXt-LFDS was not exceeding its predecessor.

Most of the current issues can be translated to the interface design and the not self-explanatory functionality of the embodiment. Given that the NXt-LFDS uses a touchscreen with interactive widgets, the monitor looks more cluttered showing not only the iterative results but also functionality features. The LFDS makes use of a modified numpad with various function buttons.

The overall performance of the LFDS in interaction and processing is rated better and quicker than the new machine. The embodiment is different, the monitor is further away from the user, and the workbench/sensorial space is easily accessible for free physical tactile exploration. Interaction seems to be more intuited by design and appearance. Whereas the embodiment of the NXt-LFDS is esthetically more pleasing, the functionality and interaction seem to ask more concentration and understanding from the users.

The potential visual overload and closeness of the touchscreen appear to have a direct impact on the usability and performance. Even the relative easy adjustment of the monitor position does not effectively contribute to the initial uncertainty and discomfort of the user. However, during and after the testing, users seemed to enjoy the touchscreen interface and GUI. It was a matter of experience and understanding of the interface modalities that contributed to the increase in performance over time.

The LFDS is perceived more "intuitive" than its counterpart in the comparison; this is probably because of its simple and low-tech appearance in conjunction with the self-explanatory interface devices (e.g., numpad, red capture button, and foot pedal). This correlates with Shirky [29] who states that "…you don't need fancy computers to harness cognitive surplus; simple, cheap, flexible tools are enough." In video interaction analysis, we witnessed enjoyment and signs of flow in interaction and user behavior.

This directly relates to the findings by Csikszentmihalyi on clarity of goals—knowing how well one is doing, balancing challenges and skills, merging of actions and awareness, and avoiding distractions; forgetting self, time, and surroundings directs to flow and happiness [28].

The fast number of iterations made by the participants showed a plethora and serendipity in ideas and possible solutions for the concept design of a hydrogen car. Working with tangible and tactile artifacts and objects in combination with virtual artifacts made the participants perform and transform a huge variety and diversity in embodiments, assemblies, and structures.

Much reflection-in-action hinges on the experience of surprise. When intuitive, spontaneous performance yields nothing more than the results expected for it, then we tend to think about it. But when intuitive performance leads to surprises, pleasing and promising or unwanted, we may respond by reflection-in-action [8].

To continue the development of the NXt-LFDS, recommendations and improvements have been made for the redesign of the GUI, functional structure, and embodiment of the machine.

Another important aspect in the HDT design processing sequences is the steps taken parallel, during or after the fuzzy front end (fuzzy mode); this is the logic mode to review (i.e., select, sort, and stack) and followed by decision making of tagged results or possible concept solutions. The fuzzy mode affords the externalization and generation of iterative ideation, such that all thoughts and creative output are represented and transformed into virtual realities.

This metamorphosis provokes material consciousness in three ways: through the internal evolution of a type form, in the judgment about mixture and synthesis, and by the thinking involved in a domain shift. The seduction of computer-aided technologies (CAx) lies in its speed, the fact it never tires, and indeed in the reality that its capacities to compute are superior to those of anyone working out a drawing by hand [23]. The logic mode entails the review mode and affords the choice architecture to synthesize the ideas, to create virtual concepts for individual or collaborative sharing (i.e., web, cloud, or intra). This modality can be used any time through the duration of the processing; iterations can be collected and assorted for mixed or blended conceptualization of the final concept representation [12,19,20,27].

Most of the users (novice) did not understand or were clear about the possibilities and/or functionality of this specific modality. The current software on the NXt-LFDS is not "robust" enough to support the interaction fluidly and congruously. Therefore, this feature felt sluggish and showed latency during use. This problem might have had some implications on the motivation and activity of the participants.

To conclude, we paraphrase Prensky [30]: "We the Game, we the CAx, we the People, we may well 'make sense of novelty through the lens of history,' defining 'new technologies in terms of older, more familiar ones,' [31] but that process can also be reversed. The transitional can operate both ways with adaptations" [32]. We shall not cease from exploration, and the end of all our exploring, will be to arrive where we started, and know the place for the first time [33].

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