Thinking in space: concept physical models and the call for new digital tools

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Abstract.

This paper investigates the potential benefit of "gestural" and haptic (touch) interaction and stereovision in computing for three-dimensional form conceptualisation and spatial reasoning in the germinal phase of the design process. Specifications for suitable digital support will be extracted from current design practice in concept design with the focus on "physical concept models". Potential advantages and limitations will be briefly discussed and general directions for research outlined.

1. Background

Recent research on creativity and computers has focused on the creation of new applications and devises to assist designers during the early conceptualising stage of the design process, the germinal phase. Through literature searches, most of the available data focuses on product, industrial and engineering design, as these are the main areas that can attract industrial and commercial funding for research. None-the-less, from analyses of the use of traditional tools for 3D object conceptualisation during the early phases of design (sketching and models making), our conclusions are relevant to all designers, as the germinal phase entails mental processes that are similar amongst the different design domains.

Although computers have a great potential as catalysts for creativity, current design practice shows that many designers still prefer to use non-digital media, that is sketching and models, during conceptualisation[1]. This practice is wide spread, and appears particularly contradictory in product/industrial design environments, where the final design output is required to be digital[2], as poorly managed design flow can cause additional costs and time losses among design firms. While industry-based research attempts to restore fluidity and coherency in the design process to improve production, from a designer's perspective, the main issue to be addressed is the interaction between designing activity and computer tools. Current computer tools fail to support the germinal phase where computers would otherwise be regularly used for conceptualisation among designers in general. This would include those unrestrained by the needs of industrial production. Applied artists as makers are not tied to the need to digitise their designs, and would only use computers where they offer advantages over traditional tools and have features relevant to their activities. Since computers provide many positive functions such as portability, flexibility, data storage and so on, the reason for their inappropriateness in the germinal phase is perhaps to be found in current modalities rather than in their inherent qualities and potential. It can be hypothesised that developing computer applications around user specifications would increase usability.

Computers are flexible and programmable, and can theoretically adapt to different contexts. This positively differentiates them from other traditional media. Therefore the usual rationale of designers adapting to computer interfaces should be put differently, that is, how should computers match their users needs. Improvement in the design experience would then arise as a consequence of a more considered encounter between the digital media and the designer's requirements.

1. Introduction

In industry the manufacture of designed objects and products has rapidly shifted towards the use of computers for almost every stage, imposing a conflict between digital processes and design practice.

Current computer-based tools tend to stifle rather than support the creativity of users: The counterintuitive interfaces of computer aided design (CAD) software and the lack of spontaneity afforded by the modelling methods can prove disruptive.[3] Highly digitised industrial processes tend to overlook the role of the designer in the process itself. There is an increasing awareness that "the efficiency and the quality of future product developments depends upon the gap being closed between quickly developing technologies and cognitive abilities and limitations of the designer."[4]

This statement particularly applies to the germinal phase where the generation of ideas and creativity has a central role.

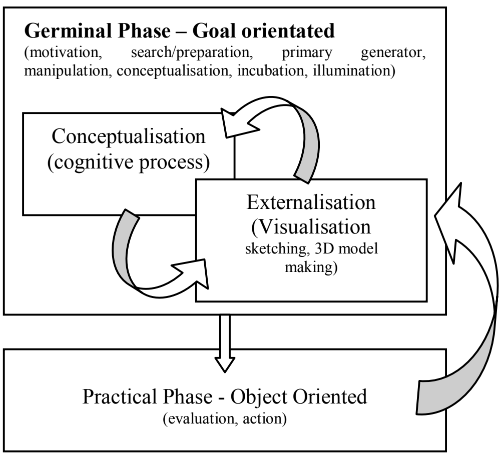

Fig 1. The Creative Process

There is an increasing requirement to integrate digital and conceptual designing and for computers to adapt to the user instead of the user adapting to computers. While there is this gap between the cognitive needs of the designer and traditional CAD, the use of sketches and physical models remain the preferred medium during the germinal phase of the design process.[5] A survey conducted among practising product and engineering designers in 2001 revealed that in 93% of cases a computer-based output was required from the design department, but a large amount of projects (73%) would start with conceptualising using sketching or rough physical models.[6]

It could be argued that this is acceptable as artefacts and ideas can be transferred to a cad system at a later stage, when digitalisation becomes necessary. Nonetheless the effective utilisation of digital tools from the very early phase could better respond to industries' needs and be beneficial to the designer's cognitive demands.

For industrial processes, "later stages of product development such as […] manufacturing planning require the product model to be available in electronic form. By consequence it would be advantageous to derive those electronic models from CAID (Computer Aided Industrial Design) systems rather than to convert from traditional media into digital forms". [7] The results of a survey investigating CAD requirements in design show that a tool for "computer-based, early evaluation and analysis of design alternatives" was ranked as the most urgently needed.[8]

Additionally, it would be desirable to enhance the conceptual design stage through the development of suitable computer tools. This would be an advantage for all designers and for industry, since "decisions made in conceptual design have a very large impact on the overall product success ".[9]

The first step is therefore a better understanding of the reasons behind the use of traditional media during conceptualisation despite the advantages brought by digitalisation. Ideally, crucial aspects from non-digital tools should be integrated into future computer-based Tools. [10]

Consequently this paper analyses traditional tools and their use for 3D form-giving and shape creation within the germinal phase.

This will allow for realistic user requirements to be tested against available technology and subsequently translated into specifications for future software implementation.

2. Sketches, Physical Models and the design process

Both sketching and modelling are still perceived as necessary among designers working with 3D forms. According to Romer et al.[11] rough sketches on paper are as widespread as CAD in current product design practice. It has been argued that sketching is important in designing, as it facilitates visual discovery, mainly through the supporting complex figure and form 'restructuring'.[12] Sketching provides visual external references, which enhance communication and clarification of design ideas to others and to the designers themselves.[13]

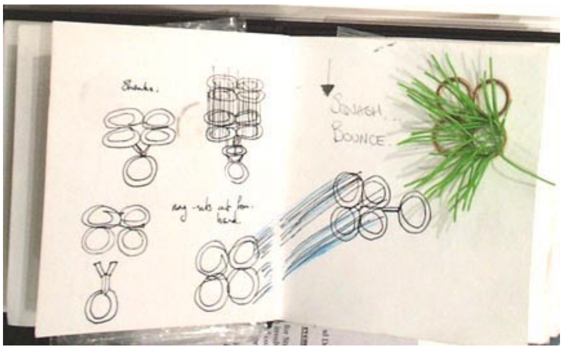

Fig 2. Sketch book and model: ideas for jewellery.
Wendy Donaldson,
4th Yr. Student, Edinburgh College of Art, 2002

Schön and Wiggins have described the process of designing through sketches as an active "conversation" between the designer and the design problem.[14] Sketches dynamically evolve, with the designer's ideas, from ambiguity, abstraction and a conceptual approach towards a structured and concrete representation of the solution.[15] Central to this process is the reinterpretation through "emergence" of new ways of seeing the drawing[16].
In order to be employed successfully sketches should match the repertoire of activities and images in the designer's mind.[17] Since it is necessary to become an expert to clearly describe on paper a complex 3D form, the question arises if sketching is the more appropriate means for reasoning on 3D shapes, particularly for novice designers. Pedagogic studies suggest that a natural alternative to sketches could be modelling, since children would spontaneously move towards 3D objects when presented with relevant design problems.[18] Although the popularity of sketching is certainly justified by its low-cost, availability and immediacy, whereas producing models can be time consuming and expensive, nonetheless it could be argued that the two-dimensionality of sketches has limitations, notably when dealing with 3D space. Additionally, the sense of engagement provided by models has been shown to be "qualitatively different to that provided by drawings, whether produced by hand or by CAD."[19]
Since the perceptual experience of a physical three-dimensional object is substantially different to the perception of a 2D representation of that object, modelling activates a different set of skills.[20]
Hence three-dimensional physical models still occupy a niche in design practice as they seem to serve specific purposes.
Romer et al. state that "[…] Physical models are used relatively often in the early stage, therefore, it seems that there are certain situations in which only physical models provide certain functions and therefore, such effort is regarded as necessary."[21] It could be argued that those functions promote understanding, for "models are made to answer specific designers' questions: once the question has been answered the model is wasted and its value resides in the understanding that it brought to the design process."[22]

According to design methodologies, the design an iterative sequence of sub-processes, characterised by divergent and convergent activities. Divergent activities lead to the creation of a series of alternative ideas, which are subsequently evaluated and selected through convergence, to obtain a solution. That solution might be re-evaluated and refined through iterative analysis and synthesis, divergent and convergent processes.

Different types of physical models offer some sort of support to both convergent and divergent activities. Accordingly to Lennings et al. convergent activities are well supported by Rapid Prototyping (RP) systems using proof-of-concept models, while a different type of model is needed to fundamentally support divergent activities.[23]

Fig 3. Sketch models in card: ideas for jewellery.
Jenny Deans,
4th Yr. Student, Edinburgh College of Art, 2002

A physical model that supports divergent thinking should retain the qualities of early sketches, and additionally offer the advantage of being three-dimensional. As described by Lennings et al, a physical concept model should be "easily changed", flexible and provide true "real-time feedback" as opposed as the snapshot in time offered by RP. It should also "help the designer to think in space". [24]
Those specifications focus on the interaction between model and designer, and suggest that this direct interaction aids "thinking in space".
This dialogue is echoed in Broek et al. where they state that physical models serve the purpose of "experiencing shape, shape details, shape compositions and functionality. Having a 3D

physical model, it is within an instant that all shape relations come visible and can be seized." [25]

Ken Hinckley et al.[26] point out that in general, people are good at experiencing 3D and experimenting with spatial relationships between real-world objects, but possess little innate comprehension of 3D space in the abstract. People do not innately understand three-dimensional reality, but rather experience it.[27]

3.1 Physical Models in literature: an overview

In order to further clarify types of models involved in 3D-shape reasoning it could be beneficial to briefly describe categories and use of physical models in design, bearing in mind the bias towards the domains of industrial and engineering design.

Various classifications of physical models are found in literature.[28] Models can be sorted accordingly to materials (clay, cardboard, paper, foam, etc.), level of complexity (simple/complex models)[29], building techniques (carve away, building-up)[30] and technologies (Rapid Prototyping or hand made models). Finally, models can be sorted accordingly to their function in the design process with slight variations in attributed definitions and specific boundaries for model categories dependant partly on different materials and techniques used in different design domains. For example, "industrial designers tend to create models themselves and use whatever materials and tools are available and convenient"[31], while automotive industries tend to use clay as described extensively by Tovey.[32] Difference in tools and materials reflect needs that are specific to the discipline. Sculpted models might be made in early product design where refined shapes are desirable, whereas architectonic models afford a crude shape definition but offer a hollow interior into which to fit and test mechanic and electronic components. [33]

The requirements of applied artists will differ from those of engineering designers, as the latter is usually more concerned with technical problems and less with aesthetics. This leads to different approaches to modelling with different types and materials used to address specific questions. Nonetheless, it can be argued that models used for similar purposes will probably show common key-qualities "cross-discipline".

Therefore it seems to be more appropriate to describe the function of models, based on their relevance to specific areas of the design process.

3.2 Physical concept models and their key features

A fundamental distinction can be made between models whose "function" is to be used in the germinal phase and models for the detailing stage, as found in relevant literature.[34]

Models used in the germinal phase will generally be called Physical Concept Models (PCM). They are often described as "simple" as opposed to "complex" models used in later stages when the design is developed and can be simulated in detail[35].

Additionally, as found in literature PCM will generally exhibit a certain degree of fuzziness.[36]

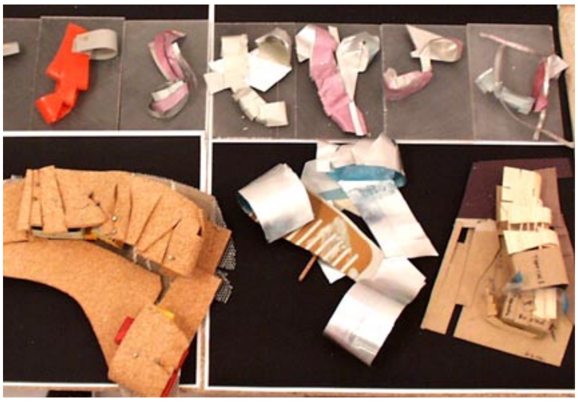

Fig. 4. Physical Concept Models: variety of materials (cork, card, foil, pins) to explore ideas for brief for building.
David Edwards, Final Yr. in Architecture at Edinburgh College of Art 2002

Vagueness of PCM has been associated by analogy to that of sketches.[37] Since the importance of ambiguity in sketches has been theorised as being a main resource for visual discovery,[38] fuzziness of early 3D models is often regarded as a fundamental feature. Vagueness of early models depends on missing elements yet to be defined, but it is also imposed by factors such as cost and time. At the early stage a complete simulation is both impossible and unnecessary, therefore the model is used to evaluate specific aspects.[39] It is unclear if this has to be classified as a "de-facto" attribute or as a positive quality. At any rate, detail is not a priority in early physical models, and this should be included among the key-features of PCM.

3.3 Functions of physical concept models

Since this paper specifically focuses on the early phase of the design process, PCM will be analysed in detail as follows with the main categories based on "function", as found in Lennings et al.[40]:

- Shape models
- Functional models
- Physical Behaviour testing models
- Presentation models
- Models for stimulating group discussion.

Functional and Physical Behaviour testing models involve a simulation of mechanical, functional or physical aspects. Presentation and discussion-stimulating models act as a catalyst to enhance communication to outsiders or among team members.

Fig.5. Shape models for lounger/chair: to explore shape and function using solid carved forms.
Thomas Knott, Final Yr. in Furniture at Edinburgh College of Art, 2002

Shape models "represent the outer appearance of the design, and are meant for visual, tactile and ergonomic evaluation. Important are the advantages of touching, feeling, easily looking from all sides, in one word the 'palpability' of the physical model." [41]
Shape models, as defined here, seem to be the type most directly involved in reasoning on shape through direct interaction.
The relevance of shape models for conceptual design has been clearly suggested in Broek's survey on physical models for product design.[42] The same survey shows that half of the interviewees produced hand-made shape models in-house; this has been interpreted as an indicator of the relevance of these models for concept design.[43] Later in the same study it was proposed that hand-made models are mainly used "to stimulate and to support designing activities and creativity" for concept design[44], and opposite to detailing (convergent) activities and rapid prototyping. Those findings suggest the relevance of manual activity for reasoning on forms. Touch in particular represents our natural "interface" to the real world in the making of objects. Applied Artist David Prytherch indicates touch as being "integral in all parts of the maker's sensory loops", as well as representing "the only means of response to any information" (during "making"). [45]

4.1 Interaction with the physical model
The characterisation of the designer as “thinking with their hands” while creating or manipulating physical models echoes the sentiment of Schön when he described the act of freehand drawing as a conversation with the image.[46]

An observational multi-year study on engineering design students and professionals[47] shows that physical objects play a relevant role during concept design, as designers appear "active and opportunistic in seeking out physical props to help them think through design problems and communicate ideas". In the same study it is argued that "design is heavily dependent upon references to physical objects and gesturing with physical objects". [48]
Physical models might support spatial reasoning for they "exist" in space. It seems that their inherent 3D structure allows for the experience of that space through vision but also, as it has emerged, through manipulation and haptic (touch) interaction. The importance of manipulo-spatial activity, that is, the combination of mental and motor processes, has been recognised in research on industrial design.[49]
The importance of action in visual processing and the highly integrated nature of visual and motor representations"[50] has also been suggested by recent experimental findings[51] in cognitive psychology.
Additional research by Brereton et al. suggest that the "tangibility" of the hardware, and thus the possibility to be "appreciated by at least two […] senses, often more", is relevant to the design process. Gibson has long argued that information from a variety of feedback channels is crucial to our understanding of space.[52]

4.2 Two-handed physical interaction
Physical interaction with objects often happens with both hands, and the modality of two-handed exploration seems relevant for shape perception. It has been claimed that the feedback on shape that the designer obtains is amplified by the use of both hands "and, through these actions, the coupling of his mental imagery with the 3D model are made".[53]
This observation finds a sound argument in Guiard’s[54] psychological analysis of human skilled two-handed action in right-handed subjects. Guiard's "kinematic chain" theory has been summarised by Ken Hinckley et al.[55] as follows:

- Motion of the right hand typically finds its spatial references in the results of motion of the left hand.
- The right and left hands are involved in asymmetric temporal-spatial scales of motion (right hand’s motion tends to be higher in precision, with higher temporal frequency and smaller spatial amplitude than the left hand. The left hand tends to move slower and on a wider scale)
- The contribution of the left hand to global manual performance starts earlier than that of the right” (e. g. sewing) [56]

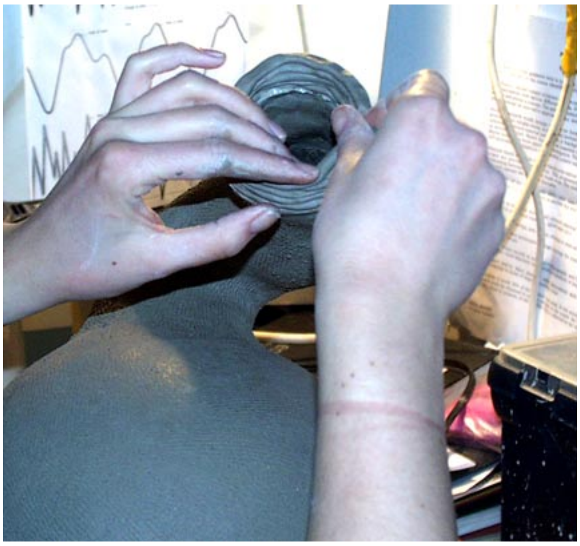

Fig. 6. Co-operation of the two hands: Ceramic student working on clay form. Edinburgh College of Art 2001

The kinematic chain theory could be applied to the making activities of designers. Guiard's theory suggests co-operation of the two hands in defining a spatial "frame" for actions, and the correlation between using of both hands and increasing performance.

5. Specifications

As anticipated, specifications for suitable digital support for 3D modelling within the germinal phase will now be extracted from the above analysis.

The hypothesised support will be referred to as "tool" since its specifications are identified by general functions.

Specifications have been divided into general and technical. General specifications attempt to define qualities of the tool from a functional perspective, taking into account cognitive needs of design, both general and specific, as well as requirements dictated from the context of use, that is, the design practice domain and associated industrial requirements.

Technical specifications evaluate which technology could better embody the proposed general specifications.

5.1 General Specifications

Overall, the hypothesised tool will respond to the specific cognitive need of the designer, that is, "thinking in space" effectively. Previous findings suggest that a "tangible" experience of three-dimensional space provides advantages in its perception. As extracted from literature, that experience might be enhanced by multi-sensory appreciation. Vision, manipulo-spatial and gestural activities (particularly involving two hands) seem to increase information gained about an object in space.

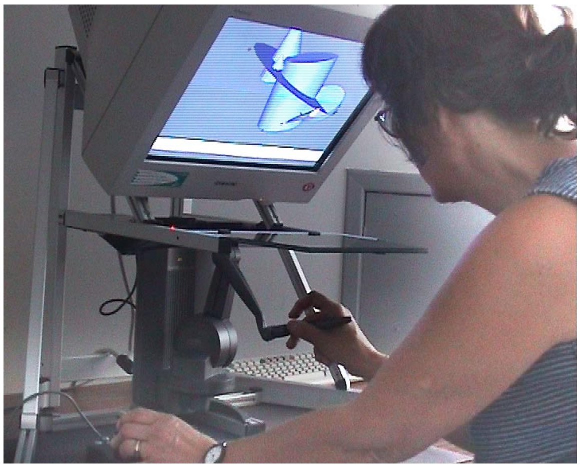

Fig. 7. Project study: manipulation of reflected screen image by dominant hand using force feedback device, and rotation and zooming by non-dominant using secondary device.

Hence, a first general set of tool requirements could be summarised as follows:

A Tool is "tangible" in space

- Tool allows perceptual "experience" of space
- Tool affords multi-sensory appreciation
- Tool affords manipulation / gestures
- Tool affords two-handed interaction

Additional specifications identify the main functions performed by supports to the germinal phase as currently used.

As discussed in previous paragraphs, available digital tools lack supporting divergent activities such as the quick generation and evaluation of alternatives. The most popular support for divergent activities is sketching, as it offers ease of use, unencumbered / fast access and quick production of results. Rough models are used in the same fashion, to evaluate specific aspects of a design problem, but they are relatively costly and time-consuming and therefore used more sporadically. Additionally, immediate (continuous) feedback for evaluation (e.g. manipulating physical models) is preferred to accuracy at this stage, as fluency supports the stream of thoughts typical of the creative process. Therefore, requirements related to the design process can be categorised as it follows:

B Tool supports divergent and convergent activities in the germinal phase

- Tool provides real-time feedback (no-snap-shots, no interruptions)
- Tool is flexible, affords easy changes
- Tool is easy to use, accessible (no-steep learning curve)
- Tool produces fast results, (immediacy over accuracy)

Finally, the hypothesised tool should meet the requirements of industry in order to be usable in design practice. Budget is always a priority from this

perspective, but apart from keeping costs directly low, other strategies such as time management can have a positive impact.
Time could be used more effectively if there was a better integration of the conceptual phase with subsequent digital phases of the process. Providing good tools for conceptualisation would also benefit the designer and therefore improve overall quality and possibly reduce the process time.
Tool specifications for use in Industry can be described as follows:

C Tool meets Industry requirements

- Tool is cost effective
- Tool integrates with digital industrial processes
- Tool reduces process time

The hypothesised tool could be described as a process catalyst since its main functions are to ease and enhance:

- the designer's cognitive activity and mental processes (continuous feedback, unencumbered interaction)
- the practical process of design creation (easy interaction and fast results)
- the overall design process (improving costs and time efficiency, as well as results).

5.2 Technical specifications

The hypothesised tool needs to be embodied in some sort of technical apparatus to test the obtained specifications against available technology to identify suitable technical specifications.

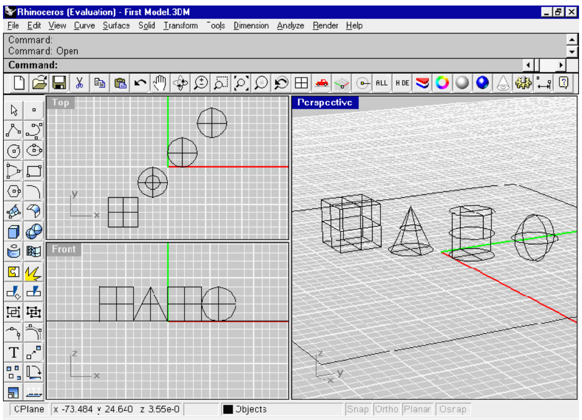

Fig. 8. Traditional CAD screen illustrating complex interface for object manipulating and navigating in virtual 3D Space.

It is obvious that the traditional desktop system does not represent the ideal setting to support 3D shape modelling as defined above for the following reasons:

- traditional CAD interfaces are far from providing ease of use and accessibility; by consequence, fluency in thinking, as well as quick visualisation, is not supported.
- traditional desktop-mouse systems are unlikely to meet any of the specifications that imply a "tangible" perception of space, such as two-handed interaction, due to inappropriate input and feedback devices.

Hence a more suitable alternative would be desirable.

It could be hypothesised that VR technology coupled with multi-sensory (e.g. haptic and visual) feedback could provide the best alternative available. Intuitively virtual reality is meant to be the best alternative to reality for "experiencing" 3D space (and therefore shapes in that space). This assumption evokes a series of controversial issues such as "presence" in VR and related difficulties for scientifically assessing subjective perceptions.[57]
Nonetheless, VR remains the best candidate (apart from reality) for conveying spatial "experience", although this has yet to be proven true due to current limitations in technology and measurement methodologies.
It is worth noting that conventional geometric modelling schemes could prove inadequate for 3D modelling in VR systems, as cognitive psychology shows that intuitive formation of ideas in the natural process of shape conceptualising is intertwined with verbal, visual and physical representations.[58]
Consequently, recent research in concept design is evaluating strategies for supporting gestures, "spatial input" and achieving a general "naturalisation" of interaction.[59] Haptic input and feedback could represent a valuable alternative to conventional geometric based modelling, and has been envisaged as a means to add a "natural" feel in computer interfaces.[60]
Additionally the sense of touch is also unique for being "be-directional". "We do not only receive input from the world with it, but we affect our environment as well".[61] Be-directionality in touch could potentially convey a quasi-continuous "input-feedback" loop, making it easier to achieve seemingly real-time feedback.
Haptic technology also allows for more direct manipulation, which could specifically be relevant to 3D shape conceptualisation. Faconti et al.[62] define haptic interfaces as "revolutionary" since they make possible direct "sensing" and modifying of virtual objects through touch.
Effective manipulation through haptic technology is difficult to achieve. Even if force and tactile feedback were implemented effectively, it would not be comparable to that of reality. The question arises about suitable compromises to be reached between cognitive demands and available solutions: "how much" reality is necessary to support tactile and force-feedback interaction for design purposes?
The answers to these questions reside with specific haptic devices with different qualities, whose suitability varies in turn with tasks and contexts. For instance data-gloves allow for exploration with the

whole hand and for tactile feedback, while force-feedback devices could offer other advantages, such as the exploitation of resting positions to support precision fine motor skills.[63]

6. Conclusions

The claim, that haptic technology could be effectively exploited for 3D-shape conceptualisation, holds promising theoretical considerations as well as unanswered questions. Analysis of current tools used in the germinal process suggests that haptic technology could contribute to a better alliance between designers and computers. First of all haptic technology could afford a less complicated interaction with digital media and improve workflow as our body represents a direct and natural interface between us and the outside world. Secondly, haptic and gestural interaction with 3D objects seems to provide qualitatively important information about them, as the use of physical concept models in design suggests. Nonetheless, currently implemented technology severely limits the quality of information attained from synthetic digital models and thereby the relevant data conveyed to the user. This raises the question about how haptic interaction in computers can be exploited in a manner complementary to that of reality. As findings obtained from current research are mainly task specific and partially dependent on technology, generalisations are difficult to make. Due to this complexity it is difficult to assess to what degree available haptic devices can support spatial reasoning.

A viable approach towards the integration of haptic devices into CAD system might be to investigate haptics as a component of the interface, within the relevant framework of spatial-input interfaces for 3D-shape conceptual design. HCI studies are needed to clarify the effects of haptics and spatial interaction on performance and on workload distribution in 3D modelling tasks.

Qualitative analysis in the form of surveys could address subjective issues such as whether the experience of space and the perception of haptics provides a more natural/unnatural, effortless/tiring effective/frustrating interaction. Additional questions on design-related tasks, such as 3D-shape creation, could also indicate whether haptic technology is perceived as a valuable adjunct to the designer's ideal for working digitally and naturally.

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