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# Physical and Virtual Tools: Activity Theory Applied to the Design of Groupware

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**Abstract.** Activity theory is based on the concept of tools mediating between subjects and objects. In this theory, an individual's creative interaction with his or her surroundings can result in the production of tools. When an individual's mental processes are exteriorized in the form of tools – termed objectification – they become more accessible to other people and are therefore useful for social interaction. This paper shows how our understanding of activity theory has shaped our design philosophy for groupware and how we have applied it. Our design philosophy and practice is exemplified by a description of the BUILD-IT system. This is an Augmented Reality system we developed to enhance group work; it is a kind of graspable groupware which supports cooperative planning. The system allows a group of people, co-located around a table, to interact, by means of physical bricks, with models in a virtual three-dimensional (3D) setting. Guided by task analysis, a set of specific tools for different 3D planning and configuration tasks was implemented as part of this system. We investigate both physical and virtual tools. These tools allow users to adjust model height, viewpoint, and scale of the virtual setting. Finally, our design practice is summarized in a set of design guidelines. Based on these guidelines, we reflect on our own design practice and the usefulness of activity theory for design.

**Key words:** activity theory, Augmented Reality, computer, configuration, co-located interaction, cooperation, design, graspable, groupware, objectification, physical tools, planning, social, Virtual Reality, virtual tools

## 1. Introduction

The aim of this paper is to explain and illustrate our design philosophy for developing graspable groupware. Our philosophy is based mainly on the concepts of *tools* and *exteriorization* found in Leont'ev's (1978, 1981) and Engeström's (1990, 1996) work on activity theory. Our practice rests on Bødker's (1991) and Kaptelinin's (1996) work, where they apply activity theory to human-computer interaction. In our construction of a system we employed a recent technology called Augmented Reality (AR). Before we began to develop the system, we studied users needs by employing task analysis methodology.

According to Leont'ev, not only is activity shaped by physical surroundings, activity in turn shapes the surroundings. When activity shapes those surroundings what happens is that *internal* mental activity materializes into artifacts. This process of turning mental activity into an object or *objectification* is what Leont'ev called *exteriorization*. While it is obvious that for any individual the moment of *exteriorization* is an important step in his or her creative design activity, it is perhaps less obvious that this is a crucial step in making ideas accessible to others. From this perspective *exteriorization* is an important social moment which supports mutual understanding in a collective creative design process.

In our design philosophy we take account of the physical and social surroundings as well as the physical and mental faculties of human beings. We draw on Bødker's (1991) and Kaptelinin's (1996) work as a basis for our design process. While we do not consider aspects of human consciousness and emotionality in human development, we note the possible connection between these aspects and human-computer interaction (Nardi, 1996b).

A vital part of our design philosophy is the tradition of AR, which enriches natural communication with virtual features. Backed up by activity theory and the usage of AR, we developed groupware for layout planning and configuration tasks; this groupware is called the BUILD-IT system (Rauterberg et al., 1997a, 1997b, 1998; Fjeld et al., 1998a, 1998b, 1998c, 1999a, 1999b, 2000, 2001; Fjeld, 2001). This system enables end-users, grouped around a table, to cooperate in the active design of a virtual setting, thus supporting co-located, instead of distributed, interaction. The multi-user functionality of BUILD-IT overcomes a serious drawback often seen with computer-supported cooperative work (CSCW) systems, namely that they are based on single-user applications[1] (Grudin, 1988). We believe that co-location is an indispensable factor for the early stages of a complex planning process. Input and output, however, can be prepared and further developed offline, using a conventional Computer-Aided Design (CAD) system. Other major projects where graspable groupware was constructed to support planning processes are the metaDESK (Ullmer and Ishii, 1997) and the Environment and Discovery Collaboratory (EDC) (Arias et al., 2000).

Section 2 introduces our theoretical background, which stems from activity theory; we discuss concepts such as *tools*, *objectification* and *collective action regulation*. The difference between goal-directed pragmatic action and exploratory epistemic action is emphasized. Section 3 describes our design philosophy in terms of AR. Task analysis and the incorporation of both physical and virtual tools are two methods which we show to emerge naturally out of our design philosophy. Section 4 demonstrates how our design philosophy was used to develop the groupware called BUILD-IT. Our design philosophy is subsequently applied to the design of tools for graspable groupware. We describe the basic principles of human interaction with graspable tools and show how such tools are developed according to the results of task analysis, whereby we focus on the challenges and problems we encountered. In Section 5, the benefits of activity theory for groupware design are discussed and a set of design guidelines is outlined.

## 2. The concept of tools in activity theory

To provide a theoretical background, we show how our understanding of activity theory has shaped our goals and the design process of AR groupware. First, our account of the *tool* concept and *objectification* is given. Then, collective action regulation is explained. Finally, we introduce two types of complete action regulation cycles for goal-directed pragmatic action and for exploratory epistemic action.

### 2.1. TOOLS AND OBJECTIFICATIONS

In the most general sense, activity means a subject's interaction with his or her surroundings. Modern activity theory originated from Soviet cultural-historical psychology (Vygotsky, 1978; Leont'ev, 1978, 1981), which in turn is rooted in both eighteenth and nineteenth century classical German philosophy – from Hegel's idealism to the historical materialism of Marx and Engels, in which the concept of activity was extensively elaborated. These roots are quite unfamiliar to most Anglo-American readers and have therefore been partly neglected (Kuutti, 1996). Yet, Engeström (1991) claims that activity theory today is transcending these origins, becoming truly international and multidisciplinary. Two results of this development are Engeström and Middleton (1996) and Nardi (1996a).

Fundamental to modern activity theory is the idea that the development of thoughts and cognitive activity requires social interaction and exchange with a physical environment. Via the process of *internalization*, social interaction turns into mental activity. Handling ever more abstract objects and concepts is part of an individual's cognitive development. Nevertheless, the physical environment remains important, since it is used for the *externalization* of thoughts and as external memory. This is particularly important for the abstract planning and configuration tasks we focus on in this paper.

Individuals are confronted with tasks that life puts in front of them and they use artifacts as tools or create tools out of their understanding. These tools then become part of the cultural context of other people. A tool mediates an activity, thereby connecting a human being, not only to the world of objects – his or her physical surroundings – but also to other human beings. At the same time the use of a tool appropriates the collective experience of humanity embodied in that tool (Leont'ev, 1982). In this sense we view the developmental processes of human beings, their physical surroundings and social culture as co-evolutionary. As Engeström (1991) puts it: "The idea is that humans can control their own behavior – not 'from the inside', on the basis of biological urges, but from the outside, using and creating artifacts".

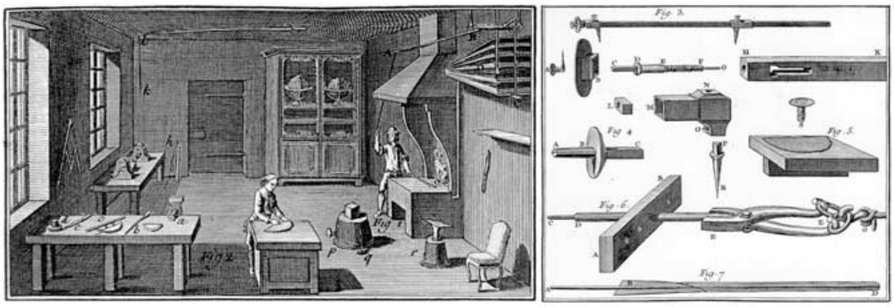


*Figure 1.* Tool production during the eighteenth century (Diderot and D'Alembert, 1778).

For planning activities Engeström's idea has been applied to artifacts and tools, resulting in sketches, documents, and three-dimensional (3D) objects or devices. (At this point in our research process, we view Engeström's artifacts and tools as corresponding to Leont'ev's (1978) *objectifications* of physical nature.) Hacker et al. (1998) describe the importance of *grasping* design ideas by sketching and by low-cost prototyping. Such methods may help to achieve design results in a faster and better way than by using abstract design processes. Physical interaction handles, for instance *bricks* (Fitzmaurice et al., 1995), can be seen as physical devices for *exteriorization* in a planning process.

To illustrate the tradition of tool development in activity theory, a historic example might be of interest. In the historical collection of the ETH library, we found that mathematicians of the eighteenth century (Diderot and D'Alembert, 1778) employed a variety of physical tools[2] (Figure 1). Modern mathematics has become even more an abstract field of study.

However, the view of tools presented above can also impose some limitations on the potential applications of activity theory. In Virtual Reality (VR) "the border between a tool and reality is rather unclear; information technology can provide the user not only with representations of objects of reality but also with a sort of reality as such, which does not obviously represent anything else and is intended to be just one more environment with which the individual interacts" (Kaptelinin, 1996, p. 64). This unclear border is a problem VR presents to activity theory; it might be solved by enriching activity theory's basic principles with new ideas from cultural-historical traditions or other approaches for studying the use of artifacts.

One answer may be found in the distributed cognition approach, in which internal and external representations of artifacts are examined (Flor and Hutchins, 1991; Hutchins 1991). As in activity theory, this approach describes how we may take advantage of artifacts designed by others in collaborative manipulation. Compared with activity theory, "distributed cognition has taken most seriously the study of persistent structures, especially artifacts" (Nardi, 1996c, p. 85). However, the two closely related frameworks show one distinct difference. In activity theory artifacts mediate human thought and human behavior and there is no intrinsic symmetry between people and their tools. Based on the 19th century debates on epistemology and on what a human being is, gaining knowledge can be seen as an individual process, a process of knowing, which can only take place in an individual. In contrast, distributed cognition puts people and things at the same level; they are both 'agents' in a system (Nardi, 1996c, p. 86). Hence, the distributed cognition approach ignores the faculties of human beings not found within computers, like motive, emotionality, and consciousness. It also ignores for computers their non-human traits, namely their ability to execute programs in a precise and predictable manner. By focusing on a common capability of humans and computers, much is lost on both sides.

Another answer is found in Bødker's (1996, pp. 151–152) characterization of the different focuses in the *use activity*:

- The *physical aspects* – support for operations toward the computer application as a physical object. The physical aspects are the conditions for the physical handling of the artifact. . . .
- The *handling aspects* – support for operations toward the computer application. . . . The handling aspects are the conditions for transparency of the artifact that allow the user to focus on the 'real' objects and subjects of the activity. . . .
- The *subject/object-directed aspects* – the conditions for operations directed toward objects or subjects that we deal with 'in' the artifact or through the artifact. . . .

In our work we understand the *physical aspects* as how to use the hardware to operate the groupware, the *handling aspects* as how to operate the groupware, and the *subject/object-directed aspects* as how to use groupware to solve a task.

Bødker talks about 'real' objects and subjects of the activity. Working with VR, the object of the activity is represented by a *virtual world*. What a subject situated within that virtual world would see, is represented by a *virtual viewpoint*. By interpreting the term 'real' in the handling aspects as 'virtual', we may overcome the limitations pointed out by Kaptelinin (1996), i.e. we may clearly define the border between tool and reality. This interpretation takes on particular importance when we develop our so-called *navigation methods* (Section 4.3.3), which are purely based on the handling aspects. In a more general way, we will use all three focuses in the use activity to structure the description of our design process (Section 4).

## 2.2. COMMON OBJECTIFICATION

In more recent developments, the scope of activity theory has broadened to encompass interaction within a community (Engeström, 1991). Since our design philosophy is centered on supporting co-located groups, this new development has been of particular interest to us. As pointed out above, a tool connects an individual to other human beings by mediating activity, thereby becoming part of a cultural context. Of particular interest to us are tools that are made or used by groups.

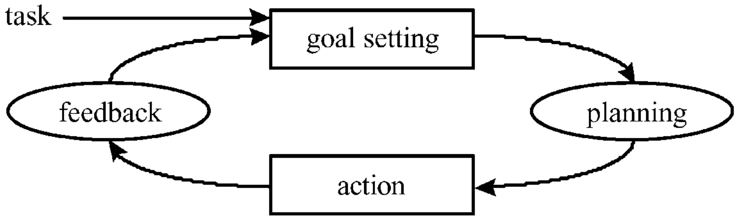


*Figure 2.* A *complete action cycle* for goal-directed pragmatic action as suggested by Hacker (1994). Action is derived from goal setting.

The individual processes of goal setting, planning, and action are transferred into*collective action regulation* (Weber, 1997, 1999). This transfer refers to coordination and allocation processes within a group. Weber introduces the term *common objectification* to mean *materialization* of collective action regulation, integrating different schools of activity theory. "The process of common objectification is understood as a process by which all (or several) members of a workgroup mutually transfer their individual knowledge, expertise, and experience into a material form. By doing this, they make their materialized knowledge available to other group members" (Weber, 1999, p. 13). First applied to industrial work groups, *common objectification* was also found to be of great importance in design and planning teams because planning tasks require even more mutual exchange of knowledge among experts (Lauche et al., 1999). The results of a process of *common objectification* can take the form of reports, design documents, prototypes, drawings, or software. Therefore, it is part of our design philosophy to facilitate the creation of such results among a group of users.

### 2.3. GOAL-DIRECTED AND EXPLORATORY ACTION

General models for goal-based problem solving were first suggested by Newell and Simon (1972). Drawing from the same sources as activity theory, action theory has focused on goal-directed action at work (Hacker, 1994; Frese and Zapf, 1994; Volpert et al., 1989; Frese and Sabini, 1985). Hacker (1998) introduced the notion of *complete action cycle* (Figure 2) for goal-directed pragmatic action, consisting of:

(1) setting the next (or first) goal in performing a task,
(2) planning according to the conditions of execution, including selection of tools and preparation of actions necessary for goal attainment,
(3) physical (or even mental) performance, and
(4) control according to the set goal via different sources of feedback.

In our work, however, we have realized that both our own design process *and* the planning task for which we are designing the groupware are not exclusively goal-directed; they also have exploratory elements. Exploratory epistemic actions (Kirsh and Maglio, 1994) are performed to unveil hidden information or to gain

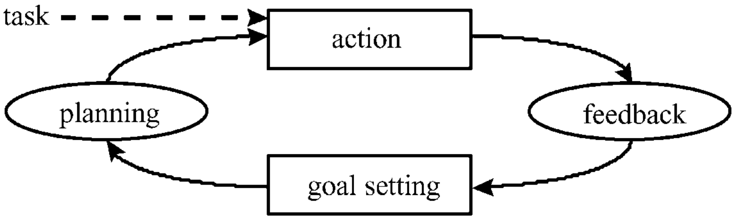


*Figure 3.* A *complete action cycle* for exploratory epistemic action. Goal setting is derived from action.

insight that would otherwise require a great deal of mental computation. Exploratory epistemic action means that no specific goal is available for initial action. Only after the receipt of feedback, which gives information on the means available, can a goal be generated. Based on this goal, a new planning stage and a new action phase can be initiated. Thereby, an alternative kind of *complete action cycle* emerges (Figure 3).

Our aim will be to design a system which fluently mediates both kinds of actions, goal-directed pragmatic and exploratory epistemic action.

## 3. Design philosophy

In this section we present our design philosophy, which is based on coinciding action and perception spaces, in its relation to Augmented Reality (AR). Task analysis and a shifting design focus between physical and virtual tools are described as two further design methods emerging from our philosophy.

### 3.1. AUGMENTED REALITY

Computer-supported cooperative work (CSCW) has enabled distant and asynchronous communication between people and has helped build ‘bridges’ in our global economy. This has brought about many well-advertised advantages, ranging from economic benefit to less status-oriented network communication. However, with many CSCW systems, users hardly interact with their physical environment. They deal only with virtual objects, which is also the case for most single-user applications. Sometimes users are even embedded in a fully virtual world, unable to draw on any attributes of the tangible physical world. Much of the users’ mental capacity is employed to adapt to the virtual world, leaving less capacity for actual task solving.

An alternative approach offered by AR is to bring the *virtual* world of computers into the *physical* world of everyday human activity. This approach includes aspects of natural communication which serve as mediators for mutual understanding: eye-contact, body language, and physical object handling. It is *non-intrusive* (Vince et al., 1999), using no gloves or helmets, and thereby respects *body-space* (Rauter-

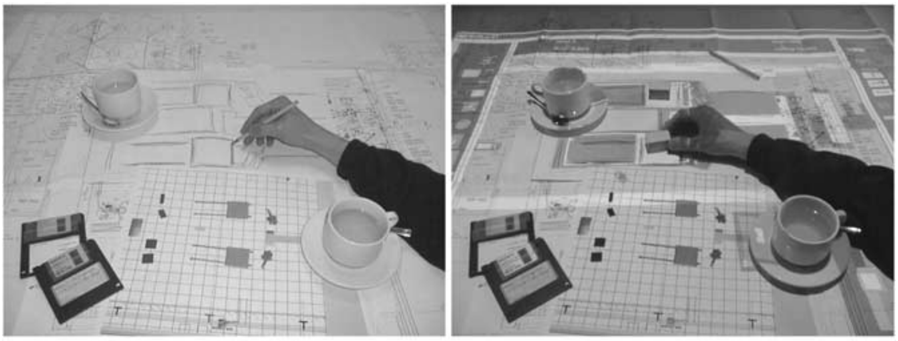


*Figure 4.* AR means that a physical workspace (left) is *augmented*, or enriched, by a virtual world (right). Even when users interact with the projected, virtual models, they do not leave the physical context (e.g. sketching) and tools (e.g. pencil).

berg, 1999, personal communication). At the same time users can still draw on the advantages of a virtually enriched world, which is of particular importance to planning tasks. The activity of planning is mainly ‘virtual’ because it involves reflecting on and modifying objects that will only exist in the future. Virtual models of these objects can be more easily changed than physical models.[3] They can be stored in external computer memory and can be visualized for interaction purposes. Thus both physical and virtual models have their rightful place in a planning process. A specific aim of our project is to study ways to integrate computer-mediated activity into the physical world. This is how we came to work within the tradition of AR, where computer-generated models and physical objects are handled in one workspace.

AR was first described by Wellner et al. (1993) and Mackay et al. (1995). The goal of AR is to “allow users to continue to use the ordinary, everyday objects they encounter in their daily work and then to enhance or augment them with functionality from the computer” (Mackay et al., 1995). According to Mackay, AR means that computer information is projected onto drawings so that users can interact with both the projected information and the paper drawing. The first brick-based AR system was described by Fitzmaurice et al. (1995). A more recent example of how AR can be used to support urban planning is given by Arias et al. (2000). Their focus is to create “shared understanding among various stakeholders . . . [by] . . . creating objects-to-think-with in collaborative design activities.” (Arias et al., 2000). Figure 4 illustrates some of these principles. Pen-based input has been studied extensively; in this paper we look at bricks as input medium.

## 3.2. ACTION AND PERCEPTION

In his ‘*Writings on the philosophy of making*’ Aicher (1996) criticizes the lack of doing by planners and the overemphasis on the reduction of real-life to inner, rational activity. He advocates a closer connection between action and mental reflection, indicating a need to enable users to bring together action and reflection in human computer interaction. For our design practice this means to “create possibilities for the users to try out the user interface through use, not only through reflection” (Bødker, 1991, p. 148). Hence, people must be able to employ their everyday motor faculties in their interaction with computers. We set out to create an interface with various input modes and tactile interaction. This demanded a user interface able to interpret a wide range of human expressions. Such interfaces need powerful computer vision methods (Rauterberg et al., 1997b).

A further important aspect of our design philosophy is the coincidence of action and perception space (Rauterberg, 1995). When handling physical objects, the space in which we act coincides with the space from which we receive (visual) feedback: we can see what we do. This is not the case for the handling of virtual models with a mouse-keyboard-screen interface, where there is a *separation* between action and perception spaces. Input and output devices are separated. To overcome this separation, Rauterberg (1995) suggested an alternative approach to interface design, an approach where action space and perception space *coincide*. Support is given by Hacker and Clauss (1976), who found that performance increases when task relevant information is offered in the same space where action takes place. This principle not only applies to visual but also to haptic or tactile feedback. Akamatsu and MacKenzie (1996) showed how including tactile feedback might improve computer-involved, task-solving performance.

### 3.3. TASK ANALYSIS AS PART OF THE DESIGN PROCESS

An integral part of our design philosophy is to gain a detailed understanding of the target activity: cooperative planning. For CSCW it is of particular importance to investigate which part of an activity is of a *genuine cooperative nature* and which part merely employs computers for *individual* work.

In the tradition of socio-technical systems theory (Emery, 1959), a task is seen as the *link* between the human/social system and the computer/technical system. Based on this tradition, it is not sufficient to take end-user expectations and preferences as guidelines for future design. Such a strategy would focus on what is already available and would be of little use for innovative breakthroughs. For instance, end-users would project their understanding of existing CAD functionality onto new interfaces without taking into consideration the whole socio-technical system they are part of. Therefore, instead of taking account of current personal and technical constraints, our analysis focuses on the task.

The strategy of our task analysis was to interview planning experts and observe their working processes, then to elicit difficulties with the predominant socio-technical system of meetings, drawings, and single-user CAD applications. The experts explained their jobs and provided examples of objectifications they used. Also, interaction with colleagues and customers was part of the interview. The results were used to make decisions about future directions in our design.

### 3.4. EXTERIORIZATION AND INTERIORIZATION OF TOOLS

Through our own design practice (Section 4.2) we made the following observations, valid from both a designer and from an end-user point of view. Before users had gained experience with physical tools (first step), user operation of the system was slow. Section 4 offers a few examples, for instance the initial bricks (Figure 8, right, in center) and the first generation virtual tool for changing model height (Figure 9). Once physical tools were available and mastered (second step), they became beneficial to task solving. This was the case for the more recent bricks (Figure 8, right) and the physical tools for changing model height (Figure 10). Based on our understanding of activity theory, we noticed that the physical tools used in the second step were an *exteriorization* of the knowledge we gained from our collective design activity (Section 2.2). Based on the experience gained with physical tools, we even saw one case where a second generation virtual tool could replace the physical ones (third step). This was the case for an elaborated virtual tool for changing model height (Figures 11–12). In the transition from the second to the third step the knowledge acquired using the physical tool was partly *internalized* (e.g. by giving our design team a common reference about the use of physical tools, even though not in use), partly implemented in the virtual tool (e.g. by mapping physical buttons onto virtual handles).

We observed that our experience is close to an idea of Kaptelinin (1996, p. 62), describing a three-step development of tool usage:

1. The initial phase, when performance is the same with and without a tool because the tool is not mastered well enough to provide any benefits,
2. the intermediate stage, when aided performance is superior to unaided performance, and
3. a final stage, when performance is the same with and without the tool but now because the tool-mediated activity is internalized and the external tool (such as a checklist or a visualization of complex data) is no longer needed.

Since the three steps we observed and Kaptelinin's idea have important points in common, we employed his idea as a justification for a repeatedly shifting design focus between virtual and physical tools.

## 4. Design example: The BUILD-IT system

BUILD-IT is a planning tool based on state-of-the-art computer vision technology (Rauterberg et al., 1997a, 1997b, 1998; Fjeld et al., 1998a, 1998b, 1998c, 1999a, 1999b, 2000, 2001; Fjeld, 2001). This system (Figure 5) enables its users to cooperate in a virtual environment for planning a real-world object, such as a room, a school, a factory, or a piazza. Grouped around a table and employing tangible physical bricks, users can select and manipulate virtual models within the setting which they are planning. This use of physical bricks represent a new way of interacting. Tethered bricks (requiring wires or cables) were investigated in the Active Desk by Fitzmaurice et al., (1995). Fitzmaurice and Buxton (1997) later

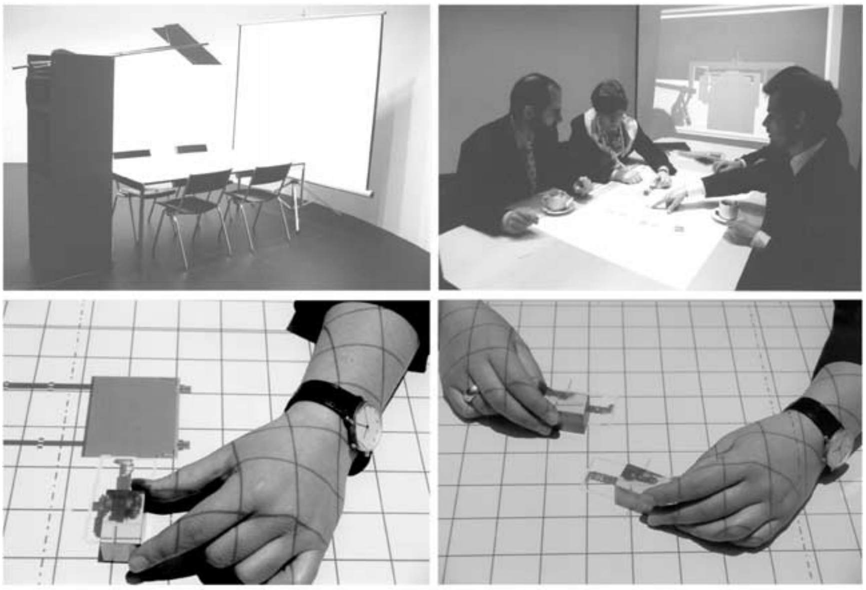


*Figure 5.* BUILD-IT consists of a rack, mirror, table, chairs, and a screen (top left). In addition to a high-end PC, the rack contains two beamers, a video camera, and a light-source. The system offers two perspectives of the same setting: a horizontal plan view for combined action and perception and a vertical side view (top right). Models projected in the plan view can be rotated and positioned using a brick (bottom left). Bimanual interaction is an essential part of the interaction concept (bottom right).

developed wireless bricks, detected by using a Wacom board. In the more recent use of tangible bricks, their surface is detected from above (Ishii and Ullmer, 1997; Ullmer and Ishii, 1997; Rauterberg et al., 1997a, Underkoffler and Ishii, 1998). It was shown that a brick-based interface is significantly easier to use and more intuitive than a mouse-keyboard-screen (Rauterberg et al., 1996).

### 4.1. BASIC ASPECTS OF THE BUILD-IT SYSTEM

Based on our discussion of tools (Section 2.1), we have chosen to structure the system description according the focuses in the *use activity* (Bødker, 1996, pp. 151–152). In this section (Section 4.1), we present all the basic aspects of the BUILD-IT system and its use. In the following section (Section 4.2) we focus on the design of tools, reflected by the *physical aspects* and the *handling aspects*. A detailed investigation of the *subject/object-directed* aspects belongs to future research.

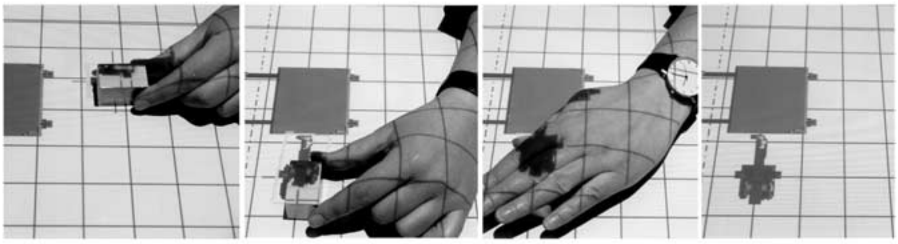


*Figure 6.* The basic steps for user manipulations with the brick.

#### 4.1.1. *Physical aspects of the system*

In our system the position and orientation of the brick on the table top is determined by a computer vision system. Reflective material is applied to the top of each brick. The bricks reflect light from a light-source to a camera viewing the surface from above. Image processing software then recognizes the bricks and determines the two-dimensional (2D) position and orientation of each (Bichsel, 1997). This information is then used to control the groupware and hence update the image projected on the table.[4] For the interaction taking place on the table, our technology respects the principle of coinciding action and perception spaces (Section 3.2). For the image projected on the screen, however, the same principle is not respeted.

#### 4.1.2. *Handling aspects of the system*

In BUILD-IT the users have two up-to-date views of the setting they are creating and manipulating at all times: the plan view and the side view. The plan view is the bird's eye view from above – which is projected onto the table. The side view is projected onto a screen near the table. In the case of the side view, a virtual camera, which can be located either outside or inside the plan view, allows the users to choose from which position the side view is to be projected. The side view can also be zoomed. In the case of the plan view, the entire projection of the setting can be shifted from side to side, rotated, or zoomed. The plan view also contains a virtual storage space for models not in immediate use. It allows users to create multiple model instances. A model instance brought back to the storage space is deleted from the views. For all handling operations affecting virtual models users draw on basic, everyday manual skills – selecting, placing, rotating, re-positioning, and fixing.

In BUILD-IT mediation between users and the virtual world follows a cyclic order (Figure 6). Users select a model by putting the brick at a model's position. The model can be re-positioned, rotated, and fixed by simple brick manipulation. A model can be de-selected by covering the brick. Then, another model is selected or the brick is left idle inside or outside the plan view. Using a material, hand-held brick, everyday manual patterns – like grasping, moving, rotating, and covering – are activated. Since all the steps in the cycle are reversible, the cost of making a

*Figure 7.* Typical multi-user (left) and single-user (right) situations. Interaction and display take place in the plan view, whereas an additional perspective is offered by the side view.

mistake is low. Thus, exploratory epistemic and goal-directed pragmatic actions are equally supported, as described in Section 2.3. However, there is no possibility of undoing, so users must keep information about previous steps in their planning process. (More comments regarding undo appear later in Section 5).

### 4.1.3. *Subject/object-directed aspects of the system*

The BUILD-IT system can be used by a single individual, but its full potential is realized as a *mediator among members of a work group* (Figure 7). Basic usage of the system is acquired within minutes. Therefore, it may stimulate people possessing different sets of skills and/or different *modes of knowledge* to work closer together and thereby enhance their (verbal) exchange. Also, since the system forces people to work with shared resources, it has a capacity to reveal potential *misunderstandings* among them. A *collective learning process* can be triggered through the unifying workspace. This was actually experienced by our design team itself during system development work.

Although we have designed a co-located, multi-user groupware system, the physical and virtual tools presented in this paper may be important steps towards a multi-site, multi-user system and therefore represent a technological foundation for CSCW. Based on standard software and hardware, the system will allow for a distributed networking CSCW system in the near future. In our projection of such a system initial configuration will be transferred at start-up time, then only brick data will be transferred at real-time. This will allow the use of standard, commercial communication channels.

### 4.1.4. *From CAD to BUILD-IT: A new tool for planning*

In most companies CAD systems have replaced drawings and physical models. This change has helped speed up the design process by systematizing recurrent tasks and reducing the monotonous work of small changes. CAD systems are more than simple drawing tools; they offer interfaces to production monitoring and quality control. In CAD systems part prices or other meta-data can be stored with 3D data. However, not all planners are yet acquainted with CAD systems. This results in a *division of labor* between planners and CAD specialists, complicating the planning process. Another drawback of CAD systems is that they are not well suited for the early stages of a design process (Hacker et al., 1998) nor for person-to-person or group communication. This is partly because they are based on single-user applications (Grudin, 1988).

Our task analysis involved 16 planning experts from the machinery and processing industries and from the field of architecture. As a result, we distinguished three possible domains of use for the BUILD-IT system:

1. *Cooperative planning among a team of experts*: For cooperative work and concurrent engineering, the BUILD-IT system offers a multi-user interface. This interface may enhance common understanding of an early planning process by offering professional tools, like advanced model height adjustment and full 3D navigation.
2. *Interactive planning with customers or clients*: In this domain the most important feature is that the customers can easily step into the early planning process and visualize their own ideas. Clients who are not used to planning – and thereby not used to 2D views – will be more at home with 3D images. The BUILD-IT system gives these users an easier access to 3D vision.
3. *Marketing*: For presentation and marketing purposes, tangible bricks may stimulate intuitive, play-like interaction. Potential clients using the system may be more involved than in conventional presentations, where interaction is fully controlled by a salesperson.

In all three domains BUILD-IT will *not replace* CAD systems. Rather, it may serve as a pre-CAD complement in the early stages of design.[5] It might also stimulate the evolution of CAD systems.[6]

### 4.2. DESIGN PRACTICE OF THE BUILD-IT SYSTEM

The challenges we faced were of three kinds. First, there is a potential perceptual problem for the users. The users employ physical bricks to design and manipulate a virtual setting which is simultaneously projected onto the table on which the bricks are sitting. Thus, the users are *living* and *acting* in two realities at once (Section 4.2.1). Designing bricks to link these realities fluently is related to the *physical aspects* of the system. Second, we encountered the technological problem of changing model height (Section 4.2.2) related to shifting focuses between the *physical* and the *handling aspects* of the system. The third problem we faced was a clear mixture of a perceptual problem for the user and a significant technological challenge to us: BUILD-IT uses 2D – or planar – interaction to access a 3D virtual setting (Section 4.2.3). The answer we found – a set of navigation tools – leverages alternative *handling aspects* of our system. The *subject/object-directed aspects* of the system (Section 4.1) will not be discussed any further.

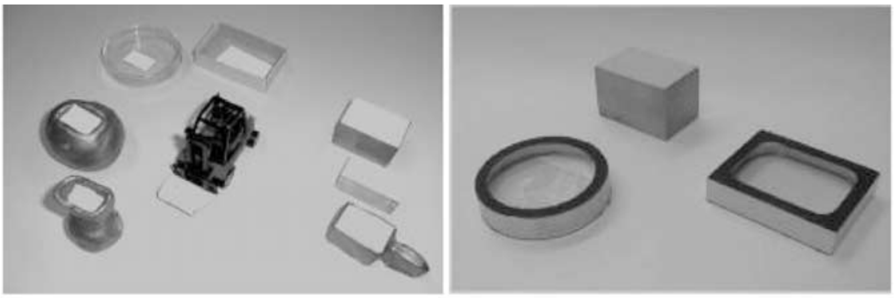


*Figure 8.* In the beginning we experimented with different bricks, based on different materials, forms, and metaphors (left). The first feasible brick was the *block* (right, in center). The more recent *circular* and *rectangular* bricks (right) are based on the principle of a *reduction screen* (see the text in this section).

### 4.2.1. *Physical aspects: Brick design*

The question related to the *physical aspects* was how to design an interface where users can move physical bricks and simultaneously immerse themselves in a virtual setting. Due to the use of reflective material for detection of brick position and orientation by the computer vision system, there is flexibility in the design of the brick size and shape. However, the bricks' shapes need to help the user keep his or her fingers or hand off the reflective area. To test different designs, we performed some exploratory brick modeling (Lauche, 1998), based on different materials, forms, and metaphors[7] (Figure 8, left).

The first feasible brick was the *block* (Figure 8, right, in center). The advantages of this shape are that users grasp the brick easily and that image detection is simple. However, due to the height of the brick, the continuity of the projected image is broken. Therefore the brick is not always suited to mediate fluently between users and the virtual world. A short experiment showed that this disruption led to a breakdown of the fluent mediation, presenting us with a problem.

To solve such a problem Kaptelinin (1996, p. 50) suggested: "deal with two interfaces instead of one user interface, with two borders, separating (1) the user from the computer and (2) the user *and* the computer from the outside world." Kaptelinin draws upon Bateson's (1972) "blind man's stick dilemma": where is the boundary between the individual who uses a tool and the external world? Does it coincide with the individual-tool boundary or with the tool-world boundary? In our case, the tool is the brick mediating between individual and virtual worlds. As an alternative to the original brick (Figure 8, right, in center), we decided to design a brick so that users perceive interaction with the virtual world, not interaction with the tangible world of the bricks.

Such a brick can be designed by employing a *reduction screen* (Voorhorst, 1999, personal communication). Such screens are *borders* placed in front of a monitor to reduce depth cues. The same idea can be used to construct the brick as an open

*Figure 9.* Setting model height by selecting (left) and moving (center) a model in the *height slice*. The model being moved is also seen in the *side view* (right).

box with a narrow black frame on the edge (Figure 8, right). For users, the bottom of the box-like brick is indistinguishable from the table surface, thus minimizing image disruption. This design also reduced the risk of users accidentally covering the reflective area.

### 4.2.2. *Shifting between physical and handling aspects: Changing model height*

Up until this point, the system placed all models on a single storey. Task analysis (Section 4.1.4) showed that potential end-users wanted to be able to position models on different stories of a building. To do this we used a three-step design process (Section 3.4) suggested by Kaptelinin (1996). In a *first step* of that process, subjects work with a virtual tool moving single models into a virtual series of stories. For this step, user performance was not satisfactory and we looked for alternatives. In a *second step* we tested physical tools which affected a particular virtual floor. A virtual floor looks like a grid-layer. This grid-layer can be adjusted upward and downward. The models selected move along with the vertical placement of the virtual floor. Physical tools improved performance but their use was too tedious (Fjeld et al., 1999). In a *third step*, a second-generation of virtual tools was developed, recombining elements of the first and the second step. Hence, the virtual floor could be handled with a virtual tool; the physical tools were no longer needed. The second step was related to the *physical aspects* of the system, the first and third steps were related to the*handling aspects* of the system. Each step is described below.

#### *Step 1: A virtual prototype for height manipulation: The height slice*

Height manipulation by means of side view handling was first achieved by copying a narrow vertical slice of the side view, called the *height slice*, and locating it along one edge of the plan view. The desired view of the height slice is selected and set by the user. Thus, models appear visible in the height slice, can be selected, and can be moved up and down (Figure 9). When de-selected, models remain at the selected height. Further details are given in Fjeld et al. (1999b).

*Figure 10.* Physical height tools: *Digit*, a box with up-down buttons and display; *Tower*, a luminous scale with up-down buttons; *Slider*, a sliding-rule with up-down handle and digital display (left to right).

### *Step 2: Physical tools as mediators for model height*

Based on physical tools (Figure 10), we explored three ways to *physically* handle model height. First, we implemented *Digit*, a digital controller which acts on a selected model and sets the model height by means of up-down buttons and provides a digital display of the height. Second, we developed *Tower*, offering the same buttons as the first tool combined with a luminous, quasi-analog scale showing selected height. The up-down buttons and the visual feedback are organized along the height axis, so action and perception are partly coincident. Third, we implemented *Slider*, a vertical sliding-rule where height is handled *and* indicated by an up-down handle. With *Slider*, handling and height cues are both organized along the height axis; thus action and perception are fully coincident (Section 3.2). Further details are given in Fjeld et al. (1999b).

### *Step 3: 'Back to the virtual': Floor handling*

The resulting solution for selection and manipulation of the models selected among multiple stories is a virtual tool called *Floor* and is a second generation virtual solution. *Floor* reuses the *height slice* from the first solution and is based on the knowledge gained with the second solution. *Floor* is handled in the *height slice*, located along one edge of the plan view. The user first selects a number of models in the plan view, forming a group. This group of selected models then moves vertically as a whole when *Floor* is moved upward or downward in the *height slice* (Figures 11–12). De-selected models remain at the last selected height. Only models at or above *Floor* are visible. Further details are given in Fjeld et al. (1999b).

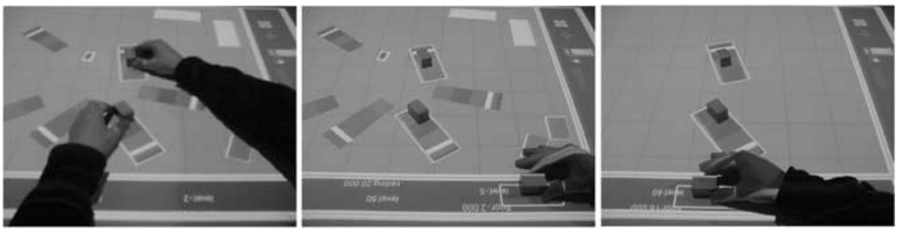


*Figure 11.* Selecting models in the plan view; selecting *Floor* in the *height slice*; raising *Floor* with the group of selected models (left to right).

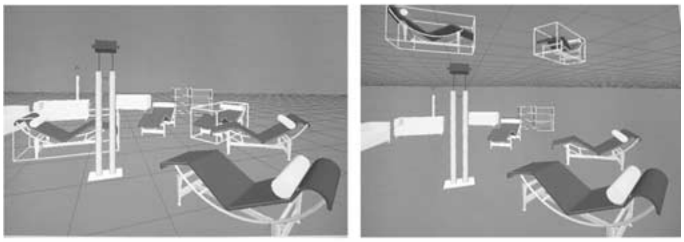


*Figure 12.* Side view; selecting and raising *Floor* with a group of selected models (left to right).

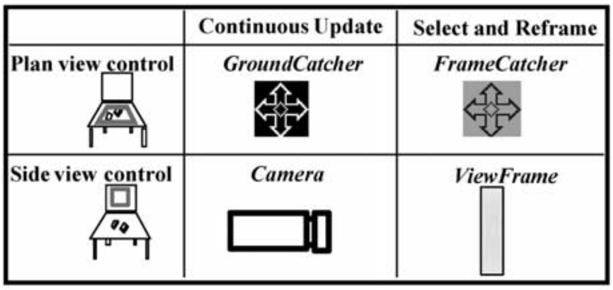
### 4.2.3. *Handling aspects: Spatial navigation*

Our task analysis (Section 4.1.4) showed that experts navigate and inspect virtual environments in a range of activities, such as urban planning and architectural walkthroughs. Depending on a user's acquaintance with virtual environments, navigation can range from exploratory epistemic to goal-directed pragmatic action. It is necessary to assume different points of view, to get an overview, and to look at things in detail in a fluent manner (Brooks, 1986).

Our answer to this need is offered by combining tangible bricks with 3D view handling of orientation and scale. Brick-based interaction in 2D has already been investigated (Fitzmaurice, 1996; Ullmer and Ishii, 1997). Also, bimanual camera manipulation and model handling in 3D graphics interfaces have been examined (Balakrishnan and Kurtenback, 1999) using two mice, a keyboard, and a screen. Here, we combine the strengths of these two approaches. The multimedia framework (MET++, Ackermann, 1996) we employ allows for full interaction in a 3D world. However, planar interaction with bricks provides only position and rotation but not height or inclination information. The resulting navigation methods are two alternative ways to bridge the gap between planar interaction and 3D view handling.

We first considered a design strategy based on the *physical aspects*, as was the case for general brick design (Section 4.2.1). This would have resulted in a physical, camera-like brick affecting the virtual side view camera. Such a solution would have required extending the properties sensed by the computer vision input.

*Table I.* The symbols used in the menu to represent the tools. There is one method (*Continuous Update* and *Select and Reframe*) per column and one view (plan and side view) per row



| | **Continuous Update** | **Select and Reframe** |
|---|---|---|
| **Plan view control** | ***GroundCatcher*** | ***FrameCatcher*** |
| **Side view control** | ***Camera*** | ***ViewFrame*** |

Based on our experience with the physical height tools (Section 4.2.2), we decided to explore virtual solutions (Fjeld et al., 1999a). The decision we took, is also supported by Ware and Rose (1999), who examined the use of real handles for the rotation of virtual models.

Hence, we investigated a design strategy based on the *handling aspects* of the system. Our strategy was to *handle* the *virtual world* or the *virtual viewpoint* (Section 2.1). This opened up two alternative design principles and both were investigated. First, in order to handle the *virtual world* – updating the view directly – we implemented the *Continuous Update* method. Second, in order to handle the *virtual viewpoint* – updating the view after viewpoint handling – we implemented the *Select and Reframe* method, where a frame represents the border of the plan view or the side view. The aim of our future research is to test which of these design principles is best suited for fluent navigation.[8]

Each navigation method consists of two tools, one for the plan and one for the side view control (Table I). The tools can be activated in the virtual storage space (Figure 13). By employing one brick – unimanual handling – shift and rotation of the controlled view can be set. By employing two bricks – bimanual handling – shift, rotation, and zoom of the controlled view can be set.[9] Bimanual handling will be illustrated here. The two methods can be combined, but only one tool per view can be activated and used at a time.

### *Handling the virtual world: Continuous Update*

Handling of the virtual world is implemented in the *Continuous Update* method and consists of two tools: *GroundCatcher* for the plan view and *Camera* for the side view. These tools work in a similar way. As soon as the *GroundCatcher* (Figure 14) is selected from the menu and placed, it locks to the setting. All subsequent handling affects the plan view. To quit the tool, the bricks are covered and removed. By selecting the *Camera* (Figure 15) from the menu, the part of the setting shown

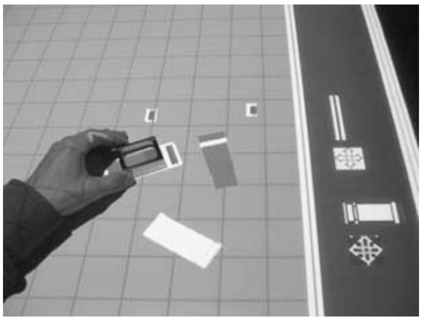


*Figure 13.* The tools are situated in the virtual storage space (menu) on the right.

*Figure 14. GroundCatcher*: Placing bricks; view handling; removing bricks (left to right).

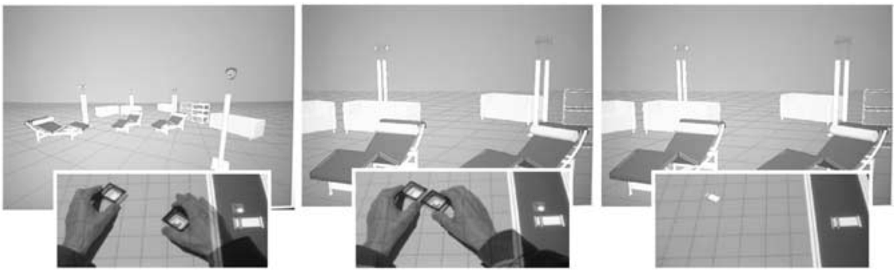


*Figure 15. Camera*: Consecutive zoom handling steps (left and center); removing bricks (right).

in the side view can be set. A zoom handle is selected with a second (here: right hand) brick. By moving the zoom handle and the camera further apart, the side view can be enlarged; by moving them closer, the side view can be focused. Covering and removing the second brick freezes the zoom. The *Camera* remains visible and accessible in the view. Further details are given in Fjeld et al. (2000).

### *Handling the virtual viewpoint: Select and Reframe*

Handling of the virtual viewpoint is implemented in the *Select and Reframe* method and consists of two tools: *FrameCatcher* for the plan view and *ViewFrame* for the side view. Both tools employ a rectangular frame representing the border of the view.

*Figure 16. FrameCatcher*: Placing bricks (left); selection (center); reframe (right).

*Figure 17. ViewFrame*: Consecutive selection steps (left and center); reframe (right).

When the *FrameCatcher* (Figure 16) is selected from the menu, the setting automatically is zoomed out to show a wider context. As soon as the *FrameCatcher* is placed within the frame, it locks to the frame. All subsequent handling affects the frame and the desired part of the setting can be selected. Covering and removing the brick triggers a reframe of the view, responding to user selection. When the *ViewFrame* (Figure 17) is selected from the menu, the side view is automatically zoomed out to show a wider context. The desired part of the setting can be selected. A zoom handle is selected with the second brick, thus resizing the window. Covering and removing the second (here: right hand) brick freezes the zoom. Covering and removing the first brick triggers a reframe of the side view, responding to user selection. The *ViewFrame* remains visible and accessible in the view. Further details are given in Fjeld et al. (2000).

## 5. Conclusion

The aim of this paper is to explain and illustrate our design philosophy for developing graspable groupware; we have focused on describing our experience with tool design for planning and configuration tasks. The aim of our work was to enable the exteriorization of end-users' planning processes. We achieved this goal by designing a graspable interface. With this interface several users can communicate and interact in a coincident action perception space and thereby reach *common objectification*. Our planning tool not only supports goal-directed but also exploratory action. We took an AR approach where virtual models are manipulated through physical bricks. In this paper we present examples from our design

*Table II.* Set of design guidelines

| | |
|---|---|
| 1. | Use physical interaction handles as exteriorizations |
| 2. | Assure coinciding action and perception spaces (Rauterberg, 1995) |
| 3. | Support body motions and simple everyday skills (Campbell, 1988) |
| 4. | Respect body-space (Rauterberg, 1999, personal communication), using less intrusive devices (Vince et al., 1999) |
| 5. | Support a clear binding between physical handles and virtual models |
| 6. | Draw on bimanual coordination skills |
| 7. | Foster exploratory epistemic action by assuring low risk in trying out |
| 8. | Support fluent navigation methods to explore 3D virtual worlds |
| 9. | Support tactile or haptic feedback (Mackenzie, 1994) |
| 10. | Give visual feedback consistent with user expectations |

practice for the *physical* and the *handling aspects* (Bødker, 1996) of our system. Related to *physical aspects*, we show how we designed brick. Related to shifting focuses between the *physical* and the *handling aspects*, we show how we developed solutions for height adjustment. Related to the *handling aspects*, we show how we developed a set of tools for spatial navigation.

From the experience we gained in using activity theory for the design of graspable groupware we distilled a set of ten design guidelines. These guidelines are presented in Table II and each guideline is discussed. Lastly, we reflect on our design practice and point out shortcomings and challenges for future work.

1. The physical handles we use are simple, non-specialized bricks. This means that the bricks do not represent particular objects like chairs, sofas, etc. For future research we want to study the use of specialized bricks. The interest in such solutions has been shown by recent experiments of handling virtual models with real handles (Ware and Rose, 1999).
2. First, the principle of coinciding action and perception spaces is fully implemented for the plan view; it is not implemented for the side view. Second, one of the physical tools developed for height manipulation (*Slider*) offers a high degree of coincidence between action space and perception space but its use is too tedious (Fjeld et al., 1999b).
3. A single brick is handled by various operations, like selecting, placing, rotating, re-positioning, and covering.
4. Our system does not rely on any intrusive devices. The only quasi-intrusive aspect of the system is that users reaching across the table interfere with the light beams and thereby cast shadows.
5. The binding between bricks and virtual models was kept uniform. However, alternative kinds of binding – called *locking mechanisms*[4] – have been implemented and will be investigated in future research.

6. By offering bimanual interaction, coordination skills from everyday handling are employed, for instance aligning and grouping. Bimanual interaction has been studied extensively by Guiard (1987) and Fitzmaurice and Buxton (1997) and guidelines may be drawn from their results.
7. Since the system is based on natural, everyday modes of communication and interaction (Section 3.1), the end-users were observed to carry out exploratory epistemic action without inhibition. Users are inherently used to a natural style of interaction and thereby perceive low levels of risk in trying out their ideas with the system. To lower the level of that risk even further, we still plan to implement an 'undo' functionality. Based on a continuous protocol, users will be able to go back one or several steps in their planning process.
8. The alternative navigation methods (Section 4.3.3) enable users to explore the 3D virtual world. It remains to discover which design principle offers higher performance. The fluent operation of navigation methods partly relies on implementation and partly on computer graphics performance. The current combination of these factors (Fjeld et al., 2000) already allows for satisfactory navigation. To explore the full space of design options, we evaluated and compared four alternative combinations of nagivation tools in terms of performance, bimanual use, exploratory use, and satisfaction (Fjeld et al., 2001). For the plan view, we found a significant difference in performance. For both views, we found significant differences in user satisfaction.
9. Tactile feedback is assured by tangible bricks. Placing a higher priority on physical handles (Ware and Rose, 1999) is a way to offer more tactile feedback. For the future Fitzmaurice's (1996) concept of *forced feedback* by *propelled bricks* could be of interest to us.
10. Visual feedback relies heavily on computer graphics performance and at present results in a delay in updating the image. With rapidly increasing performance standards of graphic cards and processors, we expect our system to give users an even more authentic feeling in the near future.

Our experience in applying activity theory has been generally positive. The theory has brought structure to our thoughts and to our design practice; the vocabulary of activity theory has proved to be useful for our discussions. However, activity theory still remains difficult to access for practitioners in the fields of design and computer science. In fact, the BUILD-IT project was also nourished by thoughts stemming from '*The ecological approach to visual perception*' by Gibson (1986). It is currently beyond the scope of our research to introduce Gibson and to systematically compare the tradition of activity theory with Gibson's approach.

In terms of the limitations of activity theory put forward by Kaptelinin (1996) and discussed in Section 2.1, our work may also stimulate theoretical development. We believe that even a virtual model of an object may serve as objectification of mental activity if it can be *handled* (Bødker, 1991). Which kind of virtuality is still perceived as exteriorization rather than disconnected outer world – or "just one more environment" (Kaptelinin, 1996, p. 64) – is an *empirical* question. We suspect that the degree of exteriorization depends on users' acquaintance with virtual tools. For the less acquainted, only the paper printout counts as an objectification, whereas for the more acquainted the virtual version – the file – is perceived as an objectification of their inner activity. Whatever the empirical outcome might be, we also look forward to more theoretical discussions on what constitutes objectification.

## Notes

1. BUILD-IT can also be used by a single person, but that usage is not the focus of this paper or the work of our group – where social aspects are being discussed and social uses developed.
2. The worker on the left straightens out a copper sheet on a marble table and controls its quality. The worker on the right (Figure 1, left) heats a steel bar at the smithy and opens a fresh-air supply. Among their tools is a beam compass, a right angle jacket, a copper fitting mold, and a copper thread dispenser (Figure 1, right, top to bottom).
3. Compared with physical, model-based layout systems, BUILD-IT offers cheaper, quicker, and more exact model representation in a virtual environment. Based on a 3D multimedia framework (MET++, Ackermann, 1996), the system can read and display geometrical forms.
4. At the moment of selecting a virtual model with a physical brick a planar relation – in terms of position and rotation – is established between the physical and the virtual worlds. We call this a *locking mechanism*. A *locking mechanism* determines how a physical brick and a virtual model stay connected from the moment of selection until the moment of de-selection. For circular and rectangular *brick forms* (Section 4.2.1) appropriate *locking mechanisms* must be defined. A particular kind of *locking mechanism* is based on one particular kind of alignment procedure. In the future we will report on our usability tests of various combinations of *brick forms* and *locking mechanisms*.
5. Employing Virtual Reality Modeling Language (VRML), individual models are transferred from a CAD system to BUILD-IT (Fjeld et al., 1998b). After a planning session, the positioned models can be returned to the CAD system.
6. Drisis (1996) predicted that new forms of interaction, for instance graspable user interfaces, could challenge the programming paradigms of CAD design.
7. Some of the tools described in this paper were related to, or based on, metaphors, such as *tower*, *sliding-rule*, *floor*, and *frame*. It may be of interest to know more about the consequences of using metaphors (Alty, 1998), not only for end-user activity, but also for the process of constructing our system.
8. Usability testing of the alternative navigation methods should call for handling of the plan view and of the side view. Due to direct feedback and a lower number of operations, we expect *Continuous Update* to deliver higher performance than *Select and Reframe*.
9. We notice that bimanual interaction underpins *exploratory epistemic latitude*, by enabling zoom. The manner in which zoom is handled, through two-handed operations, raises the topic of asymmetry (Guiard, 1987). Combinations of the factors (shift, rotation, and zoom) and their relation to one-handed and two-handed interaction will be explored in future research. Help may be found in the concept of time-multiplexed and space-multiplexed input schemes (Fitzmaurice and Buxton, 1997).

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## References

Ackermann, P. (1996): *Developing Object-Oriented Multimedia Software*. Heidelberg: dpunkt Verlag für digitale Technologie.

Aicher, O. (1994): *Analogue and Digital, Writings on the Philosophy of Making*. Berlin: Wiley-vch.

Akamatsu, M. and I.S. MacKenzie (1996): Movement Characteristics Using a Mouse with Tactile and Force Feedback. *International Journal of Human-Computer Studies*, vol. 45, pp. 483–493.

Alty, J.L. (1998): Designing Better Interfaces: Can We Learn from other Sectors? *Proceedings of the 7th IFAC/IFIP/IFORS/IEA Symposium on Analysis, Design and Evaluation of Man-Machine Systems*. Oxford: Elsevier Science, Ltd., pp. 65–70.

Arias, E., H. Eden, G. Fishcer, A. Gorman and E. Scharff (2000): Transcending the Individual Human Mind – Creating Shared Understanding through Collaborative Design. *ACM Transactions on Computer-Human Interaction (TOCHI)*, vol. 7, no. 1, pp. 84–113.

Balakrishnan, R. and G. Kurtenbach (1999): Exploring Bimanual Camera Control and Object Manipulation in 3D Graphics Interfaces. *Proceedings of the CHI'99*. New York, ACM.

Bateson, G. (1972): *Steps to an Ecology of Mind*. New York: Ballantine Books.

Bichsel, M. (1997): Personal communications.

Brooks, F.P. (1986): Walkthrough – A Dynamic Graphics System for Simulating Virtual Buildings. In F. Crow and S.M. Pizer (eds.): *Proceedings of 1986 Workshop on Interactive 3D Graphics*. New York, ACM Press, pp. 9–21.

Bødker, S. (1991): *Through the Interface: A Human Activity Approach to User Interface Design*. Hillsdale, NJ: Lawrence Erlbaum.

Bødker, S. (1996): Applying Activity Theory to Video Analysis: How to Make Sense of Video Data in Human-Computer Interaction. In B. Nardi (ed.) *Context and Consciousness*. MIT Press, pp. 147–174.

Campbell, J. (1988): Training Design for Performance Improvement. In Campbell, J., Campbell, R. (eds.): *Productivity in organizations*. San Francisco: Jossey-Bass, pp. 177–216.

Diderot, M. and M. D'Alembert (1778): *Encyclopédie ou Dictionnaire Raisonné des Sciences, des Arts et des Métiers, par une Société de Gens de Lettres*. Mis en ordre et publié par M. Diderot; et quant à la Partie Mathématique, par M. D'Alembert. Nouvelle Edition; 36 tomes (textes) et 6 tomes (en3, tabl.), 3 tomes (planches). Genève: Pellet, 1777–1781. Recueil de Planches, Tome premier, 1778.

Drisis, L. (1996): *Rationalisierung der rechnerunterstützten Konstruktion durch software-ergonomische Interaktions-gestaltung*. Düsseldorf: VDI Verlag.

Emery, F.E. (1959): *Characteristics of Socio-Technical Systems*. Tavistock Institute of Human Relations, Document No. 527.

Engeström, Y. (1990): When Is a Tool? Multiple Meanings of Artifacts in Human Activity. In *Learning, Working, Imagining*. Helsinki: Orienta-Konsultit Oy, pp. 171–195.

Engeström, Y. (1991): Activity Theory and Individual and Social Transformation. *Activity Theory*, vol. 7, no. 8, pp. 6–17.

Engeström, Y. and D. Middleton (eds.) (1996): *Cognition and Communication at Work*. Cambridge University Press.

Fitzmaurice, G., H. Ishii and W. Buxton (1995): Bricks: Laying the Foundations for Graspable User Inter-faces. *Proceedings of the CHI'95*. New York: ACM, pp. 442–449.

Fitzmaurice, G.W. (1996): *Graspable User Interfaces*. PhD at the University of Toronto. http://www.dgp.utoronto.ca/people/GeorgeFitzmaurice/thesis/Thesis.gf.html.

Fitzmaurice, G.W. and W. Buxton (1997): An Empirical Evaluation of Graspable User Interfaces: Towards Specialized, Space-Multiplexed Input. *Proceedings of the CHI'97*, ACM, New York, pp. 43–50.

Fjeld, M., M. Bichsel and M. Rauterberg (1998a): BUILD-IT: An Intuitive Design Tool Based on Direct Object Manipulation. In I. Wachsmut and M. Frölich (eds.): *Gesture and Sign Language in Human-Computer Interaction*. Lecture Notes in Artificial Intelligence, vol. 1371. Berlin/Heidelberg: Springer-Verlag, pp. 297–308.

Fjeld, M., K. Lauche, S. Dierssen, M. Bichsel, and M. Rauterberg (1998b): BUILD-IT: A Brick-based integral Solution Supporting Multidisciplinary Design Tasks. In A. Sutcliffe, J. Ziegler and P. Johnson (eds.): *Designing Effective and Usable Multimedia Systems (IFIP 13.2)*. Boston: Kluwer Academic Publishers, pp. 131–142.

Fjeld, M., F. Jourdan, M. Bichsel and M. Rauterberg (1998c): BUILD-IT: An Intuitive Simulation Tool for Multi-Expert Layout Processes. In M. Engeli and V. Hrdliczka (eds.): *Fortschritte in der Simulationstechnik*. Zurich: vdf Hochschuleverlag AG, pp. 411–418.

Fjeld, M., N. Ironmonger, F. Voorhorst, M. Bichsel and M. Rauterberg (1999a): Camera Control in a Planar, Graspable Interface. In M.H. Hamza (ed.): *Proceedings of the Seventeenth IASTED International Conference Applied Informatics*. Anaheim/Calgary/Zurich: ACTA Press, pp. 242–245.

Fjeld, M., F. Voorhorst, M. Bichsel, K. Lauche, M. Rauterberg and H. Krueger (1999b): Exploring Brick-Based Navigation and Composition in an Augmented Reality. In H.-W. Gellersen (ed.): *Handheld and Ubiquitous Computing*, Lecture Notes in Computer Science, vol. 1707. Berlin/Heidelberg: Springer-Verlag, pp. 102–116.

Fjeld, M., F. Voorhorst, M. Bichsel, H. Krueger, and M. Rauterberg (2000): Navigation Methods for an Augmented Reality System (video). In *Extended Abstracts of Conference on Human Factors in Computing Systems (CHI 2000)*. New York: ACM, pp. 8–9.

Fjeld, M., N. Ironmonger, S. Guttormsen Schär and H. Krueger (2001): Design and Evaluation of Four AR Navigation Tools Using Scene and Viewpoint Handling. In *Proceedings of INTERACT 2001*, pp. 214–223.

Fjeld, M. (2001): *Designing for Tangible Interaction*. Ph.D. Dissertation at the Swiss Federal Institute of Technology, dissertation number 14229. Available at: http://e-collection.ethbib.ethz.ch/cgi-bin/show.pl?type=diss&nr=14229.

Flor, N. and E. Hutchins (1991): Analyzing Distributed Cognition in Software Teams: A Case Study of Team Programming During Perfective Software Maintenance. In J. Koenemann-Belliveau et al. (eds.): *Proceedings of the Fourth Annual Workshop on Empirical Studies of Programmers*. Norwood, N.J.: Ablex Publishing, pp. 36–59.

Frese, M. and J. Sabini (1985): *Goal Directed Behaviour: The Concept of Action in Psychology*. London: Lawrence Erlbaum Associates.

Frese, M. and D. Zapf (1994): Action as the Core of Work Psychology: A German Approach. In H.C. Triandis, M.D. Dunnette and L.M. Hough (eds.): *Handbook of Industrial and Organisational Psychology*, vol. 4, 2nd edn. Palo Alto, CA: Consulting Psychologists Press.

Gibson, J.J. (1986): *The Ecological Approach to Visual Perception*. London: L. Erlenbaum.

Guiard, Y. (1987): Asymmetric Division of Labour in Human Skilled Bimanual Action: The Kinematic Chain as a Model. *Journal of Motor Behaviour*, vol. 19, pp. 486–517.

Grudin, J. (1988): Why CSCW Applications Fail: Problems in the Design and Evaluation of Organizational Interfaces. In *Proceedings of the Second Conference on Computer Supported Cooperative Work*. New York: ACM, pp. 85–93.

Hacker, W. and A. Clauss (1976): Kognitive Operationen, inneres Modell und Leistung bei einer Montagetätigkeit. In W. Hacker (ed.): *Psychische Regulation von Arbeitstätigkeiten*. Berlin: Deutscher Verlag der Wissenschaften, pp. 88–102.

Hacker, W. (1994): Action Theory and Occupational Psychology. Review of German Empirical Research Since 1987. *The German Journal of Psychology*, vol. 18, no. 2, pp. 91–120.

Hacker, W., P. Sachse and F. Schroda (1998): Design Thinking – Possible Ways to Successful Solutions in Product Development. In E. Frankenberger, P. Badke-Schaub and H. Birkhofer (Designers): *The Key to successful product development*. London: Springer.

Hacker, W. (1998): *Allgemeine Arbeitspsychologie: Psychische Regulation von Arbeitstätigkeiten*. Bern: Hans Huber.

Hutchins, E. (1991): *How a Cockpit Remembers its Speeds*. Ms La Jolla: University of California, Department of Cognitive Science.

Ishii, H. and B. Ullmer (1997): Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms. *Proceedings of the CHI'97*. New York: ACM.

Kaptelinin, V. (1996): Computer-Mediated Activity: Functional Organs in Social and Developmental Contexts. In B. Nardi (ed.): *Context and Consciousness*. MIT Press.

Kirsh, D. and P. Maglio (1994): On Distinguishing Epistemic from Pragmatic Action. *Cognitive Science*, vol. 18, pp. 513–549.

Kuutti, K. (1996): Activity Theory as a Potential Framework for Human-Computer Interaction Research. In B. Nardi (ed.): *Context and Consciousness*. MIT Press, p. 25.

Lauche, K. (1998): Personal communications.

Lauche, K., A. Verbeck and W.G. Weber (1999): Multifunktionale Teams in der Produkt- und Prozessentwicklung. In Zentrum für Integrierte Produktionsysteme (ZIP) of ETH Zurich (ed.): *Optimierung der Produkt- und Prozessentwicklung – Beiträge aus dem Zentrum für integrierte Produktionssysteme*. vdf Hochschulverlag, pp. 99–118.

Leont'ev, A.N. (1978): *Activity. Consciousness. Personality*. NJ: Englewood Cliffs, Prentice-Hall.

Leont'ev, A.N. (1981): *Problems of the Development of Mind*. Moscow: Progress.

Mackay, W., G. Velay, K. Carter, C. Ma and D. Pagani (1993): Augmenting Reality: Adding Computational Dimensions to Paper. *Communications of the ACM*, vol. 36, no. 7, pp. 96–97.

Mackay, W.E., D.S. Pagani, L. Faber, B. Inwood, P. Launiainen, L. Brenta and V. Pouzol (1995): Ariel: Augmenting Paper Engineering Drawings. *Proceedings of the CHI'95, video program*. New York: ACM.

Mackenzie, C. and T. Iberall (1994): *The Grasping Hand*. Elsevier, p. 15.

Nardi, B. (ed.) (1996a): *Context and Consciousness*. MIT Press.

Nardi, B. (1996b): *Activity Theory and Human-Computer Interaction*. In B. Nardi (ed.): *Context and Consciousness*. MIT Press, pp. 12–13.

Nardi, B. (1996c): Studying Context: A Comparison of Activity Theory, Situated Action Models, and Distributed Cognition. In B. Nardi (ed.): *Context and Consciousness*. MIT Press, pp. 85–86.

Newell, A. and H. Simon (1972): *Human Problem Solving*. NJ: Englewood Cliffs: Prentice-Hall.

Rauterberg, M. (1995): *Über die Qualifizierung software-ergonomischer Richtlinien*, Ph.D. Thesis. Zurich: University of Zurich, p. 206.

Rauterberg, M., T. Mauch and R. Stebler (1996): What is a Promising Candidate for the Next Generation of Interface Technology. *Proceedings of the 5th International Conference INTERFACE to Real and Virtual Worlds*. Montpellier: EC2 & Cie., pp. 95–103.

Rauterberg, M., M. Bichsel, M. Meier and M. Fjeld (1997a): A Gesture Based Interaction Technique for a Planning Tool for Construction and Design. *Proceedings of the RO-MAN'97*. IEEE, pp. 212–217.

Rauterberg, M., M. Fjeld, H. Krueger, M. Bichsel, U. Leonhard and M. Meier (1997b): BUILD-IT: A Computer Vision-Based Interaction Technique for a Planning Tool. In H. Thimbleby, B. O'Connaill and P. Thomas (eds.): *People and Computers XII, Proc. of HCI'97*. Berlin: Springer, pp. 303–314.

Rauterberg, M., M. Fjeld, H. Krueger, M. Bichsel, U. Leonhardt and M. Meier (1998): BUILD-IT: A Planning Tool for Construction and Design (video). In *Summary of Conference on Human Factors in Computing Systems (CHI '98)*. New York: ACM.

Ullmer, B. and H. Ishii (1997): The metaDESK: Models and Prototypes for Tangible User Interfaces. *Proceedings of UIST'97*. New York: ACM Press, pp. 223–232.

Underkoffler, J. and H. Ishii (1998): Illuminating Light: An Optical Design Tool with Physical Interface. *Proceedings of the CHI'98*. New York: ACM.

Vince, J., B. Buxton, L. Rosenblum, R. Earnshaw and T. Kirste (1999): Report of the Working Group on Virtual Environments, Augmented Reality and Mobile Systems, as part of a Special Report on Human-Centered Computing, Online Communities and Virtual Environments. *Computer Graphics* of the ACM SIGGRAPH, vol. 33, no. 3, pp. 45–46.

Volpert, W., W. Kötter, H.E. Gohde, and W.G. Weber (1989): Psychological Evaluation and Design of Work Tasks: Two Examples. *Ergonomics*, vol. 32, pp. 881–890.

Volpert, W. (1992): Work Design for Human Development. In C. Floyd, R. Budde, H. Züllighoven and R. Keil-Stawik (eds.): *Software-Development and Reality Construction*. Berlin: Springer, pp. 336–347.

Vygosky, L.S. (1978): *Mind in Society: The Development of Higher Psychological Processes*. Cambridge MA: Harvard University Press.

Ware, C. and J. Rose (1999): Rotating Virtual Objects with Real Handles. *ACM Transactions on Computer-Human Interaction (TOCHI)* (June), vol. 6, no. 2, pp. 162–180.

Weber, W.G. (1997): Collective Action Regulation, Common Task Orientation, and Common Objectifications in Advanced Manufacturing Systems. *Proceedings of From Experience to Innovation, Proceeding of IEA '97*. Helsinki: Finish Institute of Occupational Health, pp. 283–285.

Weber, W.G. (1999): Which Organizational Conditions Foster Prosocial Work Orientations in Teams? In M. Vartiainen, F. Avalloni and N. Anderson (eds.): *Innovative Theories, Tools, and Practices in W&O Psychology*. Göttingen: Hogrefe/EAWOP.

Wellner, P., W. Mackay and R. and Gold (1993): Computer Augmented Environments: Back to the Real World. *Communications of the ACM* (July), vol. 36, no. 7, pp. 24–26.