9

Implications of the findings

This chapter discusses the relevance of the findings of this thesis for x-ray baggage inspection, virtual window displays, Industrial Design Engineering and perceptual theories.

X-ray baggage inspection

The results of the experiments with tasks that I thought to be relevant for x-ray baggage inspection indicated that the DVWS can be used to improve baggage inspection. The experiments showed that multiple views can compensate for low image resolution and a low number of grey levels. Furthermore, the DVWS allows the observer to select a useful viewpoint, which may enhance performance on several tasks. It was expected that the image complexity of real baggage would fall somewhere between the images used for the connected-objects task (Chapter 5) and the images used for the knot-tracing task (Chapter 6). It was therefore expected that the performance of the observer would also increase with the number of viewpoints, at a rate somewhere between the results for the connected-objects task and the knot-tracing task.

The results of the connected-objects task indicated that this task can be done without a decrease in observer performance when the viewpoint selection by eye position is replaced by viewpoint selection via a knob. This result is important as tracking the eye position of an observer is difficult, requires expensive apparatus and, for reliable operation, still requires the operator to wear a distinctive marker near his eye. This last point, in particular, was expected to meet resistance from baggage inspectors. Thus, replacing the viewpoint selection by eye position with viewpoint selection via a knob seems an appropriate choice for an x-ray baggage inspection system based on the DVWS.

The analysis of Chapter 3 and the bump-matching experiment of Chapter 7 indicated that if such viewpoint selection is done by knob instead of by eye position, on-axis coupling, such as that provided by the DVWS, gives less distortion than off-axis coupling. With off-axis coupling shear distortion will occur, and this may lower performance on spatial tasks. On the other hand, the bump-matching experiment indicated that with on-axis coupling perceived depth may be compressed as compared with the real depth by a factor 2. But such a compressed depth seems acceptable, as estimating real depth sizes is expected to be of minor importance for x-ray baggage inspection.

However, given the results of the real-baggage experiment (Figure 9.1; see Chapter 8) I was unable to prove the usefulness of the DVWS for x-ray baggage inspection. No effect of the number of available views on the judgements was found. This is surprising given the promising results of earlier experiments. On the other hand, the usefulness of the DVWS has not been disproved, as there are a number of alternative explanations for the results of the last experiment.

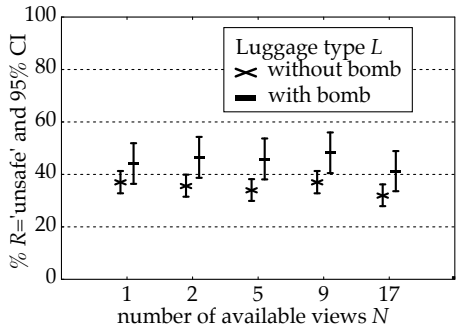

Figure 9.1. Judgements of baggage with and without a bomb. With more than one viewpoint the judgements of bomb- and non-bomb baggage differ with 5% significance (repeated from Figure 8.5).

As discussed in Chapter 8, the most serious problem is that the baggage inspection task is not operationalized clearly. Baggage inspectors are unable to explain precisely what they do to determine whether a suitcase is safe. Usually they say that they are looking for suspicious items, such as batteries and explosives. However, there are a lot of suitcases that contain batteries and may contain explosives, but are not indicated as dangerous. Furthermore, potentially dangerous objects may have an unusual appearance, not previously encountered: for example a recent development is an all-plastic battery (Simon, 1997). The minimal cues that have to be presented to the baggage inspector cannot be determined without such a clear operationalization of his task. In the case of medical tasks there is a more extensive literature about inspection of x-ray photographs. In the case of medical x-ray inspection tasks there is an uncertainty about what good inspectors are looking for (Bass and Chiles, 1990). This is similar to the findings for x-ray baggage inspection in this thesis. Future research about baggage inspection should start by operationalizing the baggage inspection task.

Another problem that might explain the results is that, with their experience and long trainingtraining, the inspectors were so used to working with a single front view that they failed to pick up the extra spatial cues provided by the DVWS. For example, they may have based their judgement on a single view. If the inspectors really fail to use spatial cues for baggage inspection, a remedy would be to train the inspectors to use this information. Because of the long experience of the inspectors, such training cannot be given just by giving a training session in advance of an experiment. Instead, this possible defect in the experiment can be evaded by giving a few inspectors intensive training. This is expensive and is probably attainable only in close co-operation with a manufacturer and users of baggage inspection apparatus.

Concluding, experimental results for tasks that were proposed as relevant for x-ray baggage inspection indicated that observer performance will increase with the number of available views. However, the experiment with real baggage showed no performance increase with increasing numbers of available views. Future research concerning x-ray baggage inspection should describe a clear operationalization of the baggage inspection task first first.

Virtual window displays

This section discusses implications of the properties of a virtual window display on the performance of an observer. The image quality (resolution and number of grey levels), cues to the flatness of the display and the coupling method (on- or off-axis coupling) were shown to affect the task performance of an observer working with a virtual window display. Furthermore, the intuitiveness of the viewpoint selection mechanism and the delay between the movement of the eye of the observer and the corresponding update of the display are important. These aspects will be discussed below, except for intuitiveness, which will be discussed under 'Industrial Design Engineering'.

Image quality

Much is known about the requirements for a static image, given some visibility requirements of objects in the depicted scene (e.g. Snyder, 1973; Olzak and Thomas, 1975; Gille, Samadani, Martin and Larimer, 1994). The availability of multiple views may compensate for low spatial image resolution and for a low number of grey levels, as was shown in the connected-objects experiment of Chapter 5. A similar effect seems to play a role with television: a film on television gives a much higher impression of the image quality than when single frames from the film are inspected. With virtual reality via helmet-mounted displays, the static image quality is far lower: typical VR image resolutions are 320 x 200 colour pixels for each eye (Holloway and Lastra, 1993). Similarly, MPEG video compression adjusts the resolution of a particular frame to the amount of difference between that frame and the next (see also Gonzalez, 1995). In spite of the common use of this effect and the extensive theoretical and technical literature about it, little perceptual investigations have been done on this effect.

Cues to the flatness of the display

Cues to the flatness of the display may have perceptual consequences. Such flatness cues can be (1) stereoscopic cues, if the display does not provide stereoscopic cues about the scene, while the observer looks at the display with both eyes, (2) a frame around the display, (3) a grid laid over the display, caused by the pixels of raster displays and (4) absence if or inappropriate shadows or shading.

According to the indirect theory (see Chapter 2), such flatness cues will flatten the depth in the 3D reconstruction made by the observer, thus affecting his performance if he needs depth cues for his task. Furthermore, flatness cues may trigger some mental mechanism compensating for viewing pictures obliquely (see Chapter 7).

In this thesis, only the effect of using both eyes while the display does not provide stereoscopic cues about the scene were investigated. X-ray images do not contain shadow cues, and the grid caused by a raster display is unavoidable given the choice to use a sensor line (see Chapter 3). A reduction screen hiding the environment and the frame of the display was used in all our experiments, because I felt that it improved the apparent depth in the scene, but I did not test this effect experimentally.

For the tasks discussed in this thesis, looking with both eyes at a non-stereoscopic display did not hinder the observers. In the bump height matching task (Chapter 7) observers using both eyes performed even better than those using one eye. This finding has an important ergonomic and aesthetic consequence: observers working via a non-stereoscopic virtual window display do not need to work with an eye-patch in order to achieve high performance.

The effect may depend on the task, as other experiments, such as described in Chapter 6 and that of Arthur, Booth and Ware (1993), showed no advantage to observers using both eyes over observers using one eye. One explanation for this difference using the direct theory is that observers used the stereoscopic cues differently for the two tasks. For the knot tracing task, the observers may have tried to use stereoscopic cues for separating the wires. As there were no stereoscopic cues in the display, performance in the two-eyes viewing condition did not improve as compared to the one-eye condition. As discussed in the task analysis (Chapter 2), the stereoscopic cues might be less relevant for the bump matching task in a natural situation (where real instead of simulated bumps were to be adjusted). Therefore the observers may have used the images from the two eyes for reducing noise instead of using its stereoscopic cues. For example, Bradshaw and Rogers (1996) indicate that two images can be used to reduce noise in the images by a factor 1.4. The ability to reduce noise may explain the higher performance of observers using both eyes as compared to observers using one eye. Thus, although the observers know that they are looking at a monitor display, the way the observers use binocular cues may be identical to what they would do if they were doing the task via natural inspection.

Another explanation, using the indirect theory, is that monocular observers get an *increased* height impression of the real bumps as compared to binocular observers. For example, absence of stereoscopic cues might place too much weight on shadow cues, causing an exaggerated impression of the height of the bumps.

Summarizing, no disturbing effects of looking with both eyes at a non-stereoscopic display were found: binocular viewing may even improve the performance of the observer as compared to monocular viewing.

Coupling method

The choice of the coupling method was shown to have important consequences, especially for distortions. Given the results of the experiment described in Chapter 7, it seems reasonable to distinguish between distortions that are seen as such (*noticed* distortions) and distortions that are usually not noticed, but nevertheless influence performance (*unnoticed* distortions). A similar discrepancy between judged display quality and actual performance given some display quality also occurs in the case of static image quality (Overveld, 1994): subjective quality ratings of a static image are largely determined by noise and blur, while these are of minor importance for performing a visual task with these images. It is only if the target contrast is extremely low that contrast is a prime determinant of the visibility of targets (Vyborny, 1997).

On-axis coupling has several advantages over off-axis coupling. I start with the perceptual advantages. Distortions that occur with on-axis coupling are usually unnoticed, while noticed distortions occur with off-axis coupling. The unnoticed distortions seem strongly related to the fact that on-axis images always are 'regular television' images. Probably the distortions in these images are not noticed because we are used to such distortions, as they occur under normal viewing conditions in ordinary television images, photographs and paintings. First, the observer will not notice shear distortion with on-axis coupling if his viewpoint is measured inaccurately, as is the case with off-axis coupling. Such shear distortion may be disrupting, for example in recognition tasks and tasks involving the use of visual angles. Second, with on-axis coupling people looking along with the observer controlling viewpoint selection do not perceive highly distorting views, but they will see large distortions with off-axis coupling. Third, on-axis coupling does not require all degrees of freedom of the observer movements to be imitated by camera

movement. As many tasks do not require all directions to be coupled, this may save the expense apparatus capable of tracking observer movements in all these directions. Fourth, with on-axis coupling the camera movements can be scaled relative to the movements of the observer, apparently without causing noticeable distortion. Such scaling can be done to increase the visible range of views, for example to improve the ability to look around an object. Such a scaling is not natural, as it will cause a conflict between the parallax cues and the proprioceptive cues (the data about body movement provided by muscle tension sensors and the equilibratory senses). Nevertheless, a scaled camera motion may be advantageous for some tasks. Fifth, in the presence of a delay no distortions are noticed, as occurs with off-axis coupling which is discussed below under 'Delay effect'. This point is discussed in the next paragraph. Finally, for some tasks viewpoint selection by eye position can be replaced with viewpoint selection via a knob without decreasing the performance of the observer.

However, unnoticed distortions do occur with on-axis coupling, even if the viewpoint is measured accurately. The results of the experiment described in Chapter 7 suggest that the fixed distance between camera and the fixation point should agree with the average (perpendicular) distance between the observer and the display. If this is not the case, the displayed scene is scaled in depth as compared to the real scene. This effect may be offset if depth scaling with on-axis coupling can be shown to be systematic, which is suggested by geometry. Such compensation can be achieved by expanding the depth in the scene before projecting it, or by manipulating the camera viewing distance and viewing angle. An advantage of on-axis coupling with regard to unnoticed distortions is that on-axis coupling is less sensitive than off-axis coupling to a mismatch between the distance of the camera and the actual distance of the observer's eye to the plane of the display.

On-axis coupling also has technological advantages over off-axis coupling. First, on-axis coupling is less sensitive to inaccurate viewpoint measurements. This may be explained by the fixed distance between camera and fixation point. Therefore, a less precise and probably cheaper eye position tracker and display system can be used. Furthermore, standard cameras provide an on-axis image, and therefore on-axis views can be acquired more easily and cheaper with real cameras than off-axis views. Off-axis coupling with a real camera will require either selection of a part of the image from a high-resolution camera with a large viewing angle, real-time image processing, or a special 'perspective correction' camera lens that shifts relative to the image plane, depending on the camera position (Figure 9.2). Such cameras with a lens that can shift relative to the image plane are used often in architecture (Figure 9.3).

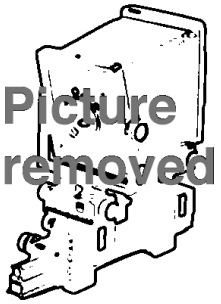

Figure 9.2. 'Perspective correction' camera capable of slanting the back containing the photographic plate. Such a camera can be used to record views for off-axis coupling (from Abraben, 1994).

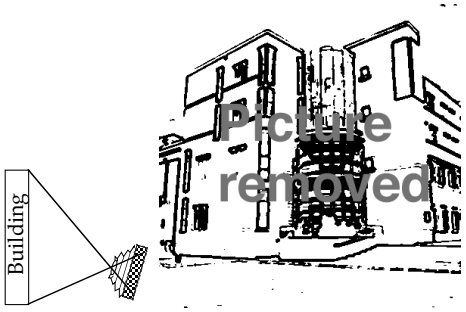

Figure 9.3a. The camera is slanted backwards to show all of the building. Vertical lines in the building run towards a vanishing point.

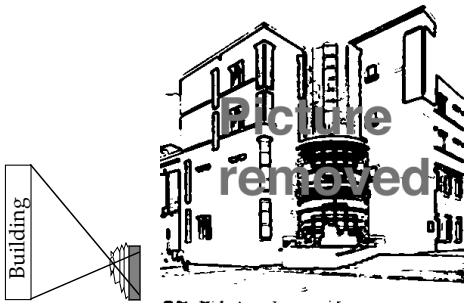

Figure 9.3b. If the back of the camera is rotated to be parallel to the vertical lines the building, these vertical lines will run parallel in the photo (Abraben, 1994).

On the other hand, off-axis coupling also has advantages over on-axis coupling. The most obvious advantage is that with off-axis coupling the displayed world forms a rigid whole with the real world around the monitor if the viewing position of the observer is coupled accurately to the displayed view. Therefore the displayed world can be fitted into the real world, or even mixed through it (mixed or augmented reality, see Drascic and Milgram, 1996). For example consider the height of the horizon in the displayed scene. With off-axis coupling the height of the displayed horizon stays at eye height when the observer moves. With on-axis coupling the height of the displayed horizon depends on the visual angle of the observer's eye relative to the display, and this does not depend directly on his absolute eye height. The direct theory suggests that this has large consequences for tasks where the horizon is used. For example, consider the stair climbing task (see Figure 2.4). Figure 9.4a shows an observer sitting perpendicular to the centre of the display, and therefore the camera is not rotated relative to the scene. Figure 9.4b shows an observer who moved away from such a perpendicular position. This causes the displayed horizon to deviate from the horizon of the environment of the display. The direct theory suggested that the observer uses the visual angles α and β (see Figure 2.4) directly to determine his ability to climb the stair. But with on-axis coupling there are two horizons, causing a conflict. However, as long as the observer's viewpoint is approximately in front of the middle of the display and at a constant distance from it, augmented reality displays can also be made with on-axis coupling (Overbeeke and Stratmann, 1988).

A less obvious advantage of off-axis coupling over on-axis coupling is that off-axis coupling seems free of unnoticed distortions, if the coupling is calibrated correctly. With on-axis coupling, such distortions affect performance if precise depth estimations or slants in depth have to be estimated (see Chapter 7).

Concluding, both on- and off-axis coupling have advantages and disadvantages. With real cameras, on-axis coupling is cheaper to implement than off-axis coupling. An important effect is that off-axis coupling and accurate calibration are necessary if no distortions can be accepted, for example if values such as apparent depth or slant have to match the apparent depth of a real scene. With on-axis coupling the apparent depth of a scene is compressed in depth as compared to the real scene, when the observer takes extremely oblique viewpoints. The distortions that occur with on-axis coupling are usually not noticed by observers, even with large inaccuracies in the measurement of the

viewpoint. This may introduce distortions, but these distortions are usually not noticed. For example, the viewing range may be enlarged to enable the observer to reach more extreme views. Such manipulations may improve observer performance. On the other hand, off-axis coupling has to be calibrated accurately to avoid distortions that will be noticed by observers. The appropriate choice for the coupling method will depend on the task of the observer.

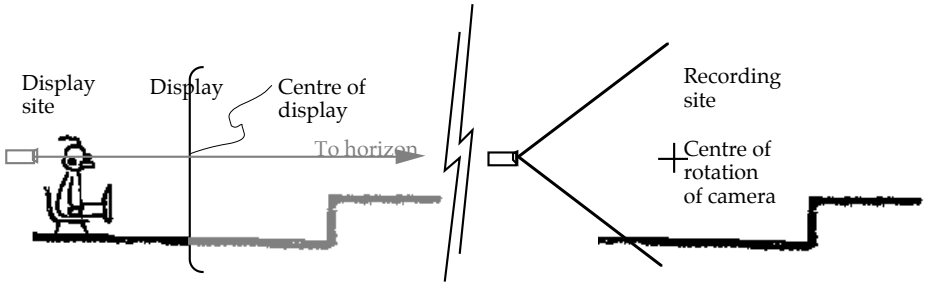

Figure 9.4a. With on-axis coupling, the camera is not rotated relative to the scene as long as the observer's viewpoint is in front of the centre of the display .

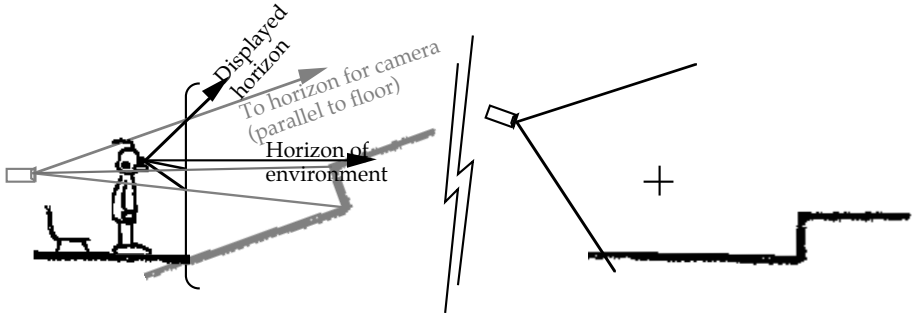

Figure 9.4b. However, as the observer moves away from this viewpoint the camera rotates according to his new position. With on-axis coupling this causes the displayed horizon to deviate from the horizon of the environment. According to the direct theory this may have large consequences, e.g. for stair climbing (compare Figure 2.4).

Delay effect

Both in the system as described in Chapter 7, in several pilot setups and in a setup with three displays instead of one (Djajadiningrat, Smets and Overbeeke, 1997) distortions caused by delays were noticed. As discussed under 'Coupling method', distortions are noticed only with off-axis coupling, and can be explained geometrically, given a delayed view at some viewpoint. I did not test experimentally the implications of such delays, because delays during viewing can be minimized, and therefore their relevance for x-ray baggage inspection is small. Given the available time for the inspector to make his judgement and the concepts of Chapter 3, the x-ray views of the baggage will have to be stored and displayed when required given the viewpoint of the inspector. In such a configuration, the delay is very small. Nevertheless, distortions due to delays were noticed in several setups, and are relevant for virtual window displays. Wloka (1995) discusses the sources and possible solutions for delays in detail.

The effect of a delay D is clearly noticeable in virtual window displays, and is different for on- and off-axis coupling. With off-axis coupling, the tops of all bumps seem to run ahead of the ground, following the observer with their distortion. As soon as the observer stops moving, they swing back to their perpendicular orientation. For example, suppose an observer is looking at the tops of two bumps that are projected with off-axis coupling. As long as he does not move (Figure 9.5a) the bumps appear perpendicular to the floor. When he moves to the right, the picture that shows the bumps straight up appears when the observer's eye has already passed the position perpendicular to the bump (Figure 9.5b). The observer interprets this image as if the bump is pointing towards him, and thus the bump must be sheared relative to the ground. When he moves in the other direction (Figure 9.5c) the perceived shear of the bumps reverses. I have never encountered this delay effect in the literature, but nor I have searched the extensive literature on delay effects systematically.

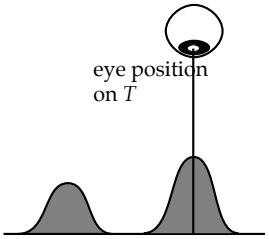

Figure 9.5a. Suppose the observer is looking at the top of a bump at moment T. If the observer does not move, the delayed refresh of the display D has no consequences.

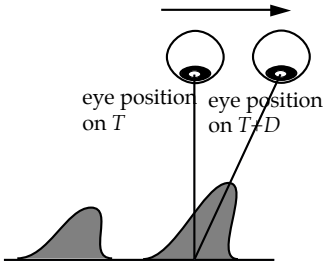

Figure 9.5b. If the observer moves the bumps appear sheared, as off-axis coupling amounts to shearing the scene and the shear is delayed relative to his eye movement.

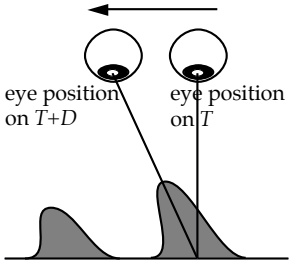

Figure 9.5c. The shear of the bumps reverses as the observer changes the direction of his motion.

The distortion caused by a delay gets worse if the observer moves faster and if the objects in the displayed scene get further away from the display plane, because the velocity of the parallax shifts increases with those factors. The delay effect had only small effects on the bump matching task, because the bumps were low and because there was no need for the observers to move fast.

With on-axis coupling, the overall movement of landscape is delayed, but the landscape stays a rigid whole. However, as described under ‘Coupling method’, unnoticed distortions may exist.

A number of factors that affect the performance of an observer working via a virtual window display were discussed. The coupling method and delays between the movement of the observer and the corresponding update of the display have important consequences. With off-axis coupling, distortions can be noticed, but as shown by task performance the distortions are small provided that the coupling is accurate. With on-axis coupling the distortions are not noticed, but have considerable effect on task performance at oblique viewpoints.

Industrial Design Engineering

Industrial design engineers have learned to solve problems concerning product development in a systematic way. They consider a number of solutions and select the most appropriate solution, considering technical, ergonomic, aesthetic, environmental and economical aspects (Smets, 1992).

For industrial design engineers the results of this thesis are important for two reasons. First, in industrial products computer-controlled interfaces providing a spatial impression are growing more important (Bouwmeester, 1996; Louwerse, 1996; van Bueren, 1997). Spatial displays are currently used in medical, military, training and data analysis applications, and are of growing importance in other applications such as entertainment, safety, public notice boards and advertising. Second, CAD systems with spatial displays are becoming a usual tool in product development. The design process itself is usually aided by displayed impressions of the planned product. Thus, both designers themselves and their customers use spatial displays. The results are important because they concern the intuitiveness of the user interface and the distortions in spatial displays.

For choosing the appropriate solution for designing a product and for presenting a spatial impression to an observer, the design engineer should consider the perceptual requirements of the task in hand, the distortions in the perceived scene that are caused by a geometrically inequivalent viewpoint and by the coupling method, and the intuitiveness of the system.

Distortions due to coupling method

One consideration when choosing a virtual window display is the coupling method to be used. As discussed under 'Coupling method', off-axis coupling is required when the displayed world has to be linked to or mixed with objects in the real world. For example if one wants to use the display itself as a piece of paper and draw on it with a pen, on-axis coupling is not useful as the displayed 'piece of paper' rotates into and out of the screen as the observer moves (Figure 9.6a). Off-axis coupling solves this problem (Figure 9.6b). However, using off-axis coupling will result in distortions for other people not coupled to the display. If other observers also have to look at the screen, for example for training or for attending a presentation, on-axis coupling seems to be the appropriate choice.

Figure 9.6a. Suppose that the observer wants to write on the displayed top plane. If on-axis coupling is used, that plane will be slanted relative to the plane of the real display when the observer is not directly in front of the middle of the display.

Figure 9.6b. With off-axis coupling the displayed planes stay parallel to the plane of the real display. In such cases where the real and displayed world are closely linked, off-axis coupling is more suitable than on-axis coupling.

Intuitiveness of the user interface

Virtual window displays can be used to provide a more intuitive design environment. Especially with a large number of degrees of freedom, viewpoint selection via a knob may be unintuitive.

For selecting a view given only one degree of freedom, as was the case with the wire detection task (Chapter 5), a slider or turning knob is sufficient and intuitive. Apparently for doing the wire detection task successfully, and probably for most tasks via a spatial display, the observer requires control over the displayed view, but he does not need to relate the parallax in the display to his proprioceptive cues. Selecting a viewpoint by eye position may even be inappropriate from an ergonomic point of view. Rotating a knob can be done faster and more easily than moving the head.

Current CAD applications offer many degrees of freedom (3 rotational axes, 3 translational axes, viewing angle of the camera, wire frame versus solid rendering, etc.) for manipulating the view, but this is usually done by providing a slider for each axis. This is not intuitive, especially if the current view is not the front view (Figure 9.7a and 9.7b).

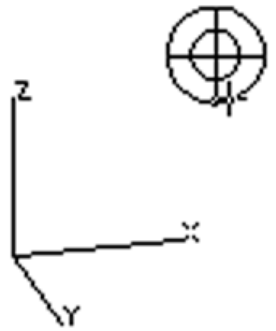

Figure 9.7a. Selecting a viewpoint with Autocad 13 and earlier versions. Moving the cross within the circle rotates the axes. These axes are related to the scene orientation. The z-axis always stays vertical, and the viewing distance has to be adjusted with another command.

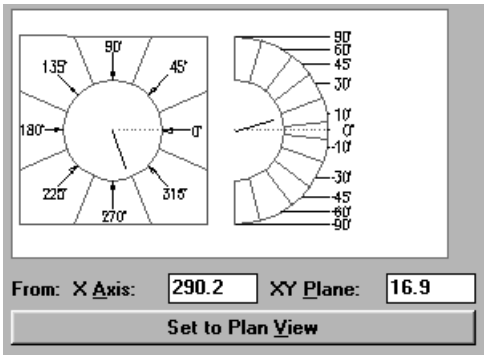

Figure 9.7b. Part of the new viewpoint selection window of Autocad 13. The element sizes in the azimuth setting (right) seem irregular. The effect of the settings on the view are hard to imagine, especially if the current view is not the front view.

There are more intuitive ways of changing the view. The interface of the 'Scene Viewer' utility from Silicon Graphics is a good example. If the cursor (the hand icon) is near the middle of the window (Figure 9.8a), dragging the hand horizontally will rotate the scene around the vertical axis. If the hand is near the bottom of the window (Figure 9.8b), dragging the hand horizontally will rotate the scene around the axis out of the display. However, the use by the Scene Viewer program of different mouse buttons to select zooming and moving forward and backward is less intuitive.

Thus, when a large number of degrees of freedom are available for selecting the viewpoint, it is hard to keep the interface intuitive (see also Djajadiningrat, Overbeeke and Smets, 1997). Coupling the viewpoint to the eye position of the observer is more intuitive.

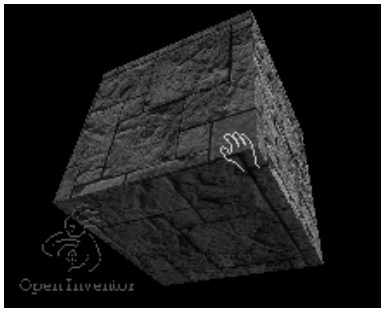

Figure 9.8a. A more intuitive way of selecting a view. Dragging the hand horizontally while it is in the middle of the window rotates the scene about the vertical axis.

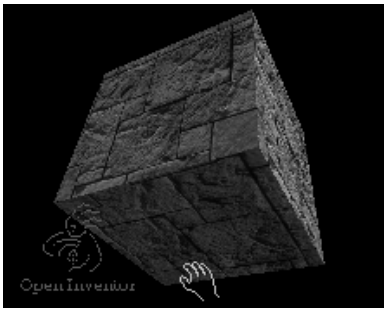

Figure 9.8b. If the hand is near the bottom of the window, dragging it horizontally results in a rotation of the scene around the axis out of the display.

Distortions due to geometric inequivalence

The distortions in the scene caused by the display system are an important consideration when choosing or using a virtual window display. Most computer aided design (*CAD*) systems do not take the viewpoint of the observer into account. Therefore the displayed scene will be distorted depending on such things as the coupling method, viewing position and camera position. This holds for both single perspective renderings and virtual window displays. For example, Figure 9.9a shows a close-up photograph of a lunchbox. It looks nearly square and higher than it would from a larger viewing distance (Figure 9.9b). Such views are generated easily with CAD programs, and in CAD programs there is usually no indication of viewing distance, which is closely related to such distortions. Such distortions are often used on purpose in advertising, and give the observer a misleading impression of spaciousness. For virtual window displays, close-up views may be appropriate when the observer is close to the display. For displays without coupling of the display to eye position, such as photographs and normal television images, a telelens may prevent such perceived distortions (Cutting, 1987). The degree to which distortions are obtrusive in static on-axis large-angle images may be minimized by image processing (Zorin, 1995; Buchroeder, 1995).

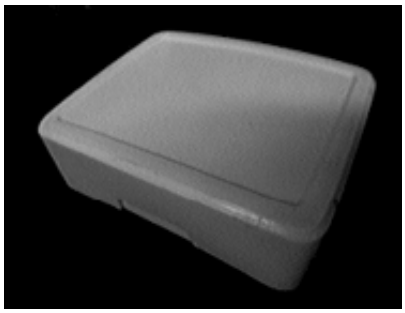

Figure 9.9a. Close-up photograph of a lunchbox. The top looks almost square, and the box looks almost half as thick as its width.

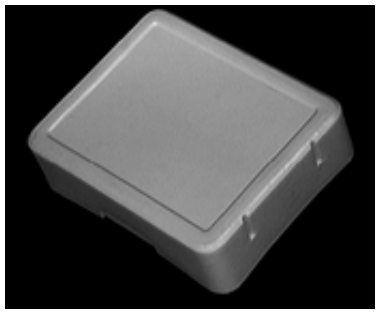

Figure 9.9b. Lunchbox photographed with a telelens. For most people, this gives a less distorted impression of the width-height-thickness ratios.

For several tasks such distortions may be unimportant, but distortion effects can be expected to be important when aesthetic judgements come into play, for example in advertising, entertainment, public notice boards and designs made on a virtual window.

As described in the previous section under 'Coupling method', both on- and off-axis coupling can cause distortions, although they are usually noted by the observer only with off-axis coupling. This makes for a difficult choice for the designer: should he convince his customers by providing a subjectively convincing image without noticeable distortions, or should he choose a configuration that is without unnoticed distortions? One aspect providing the answer is the task in hand.

Task in hand

To choose an appropriate solution for presenting a spatial impression to an observer, the task in hand should be considered. For example, virtual window displays that rely exclusively on parallax shifts cannot be used for all applications, as parallax shifts are available only when the observer moves or when objects in the virtual world move relative to the observer. It is known that with precise manipulation tasks the observer tends and probably needs to minimize his movements relative to the object to be manipulated (Voorhorst, Overbeeke and Smets, 1997). In this case stereoscopic cues may be added to the virtual window display to give the observer depth cues if the task requires this.

If a display has to provide images giving a spatial impression to the user, the design engineer can choose from a range of displays, most notably virtual window displays and head mounted displays. With head mounted displays, the observer has 2 small displays in front of his eyes. These systems are growing more important as their price is decreasing rapidly. Such systems can simulate a complete world instead of only a window with a simulated scene. Therefore such immersive VR systems are useful for designing large objects, for example in architecture. Another advantage is that in such completely simulated worlds it is possible to alter the laws of physics. For example, the body of a patient may appear transparent.

However, most applications concern a task in the real world. For such tasks, a spatial display has to provide the observer with additional data, alongside the directly visible cues from his task. In such a situation the observer has to see the real world as well, and immersive VR systems cannot be used. Mixed VR systems, where an image is merged through the real world with a half-transparent mirror, try to combine the advantages of virtual window systems with those of immersive VR. However, immersive VR still requires the observer to wear a helmet with a half-transparent mirror, and this may hinder his activities.

Many other task aspects can lead to the choice for a specific display. A number of ways of analysing the task in hand are given by Kirwan and Ainsworth (1992). To start with natural inspection, as was done in Chapter 2 for the tasks in this thesis, is possible to find the useful perceptual cues for a task, but this only holds as long as the required cues for the task can also be acquired with natural inspection. Concluding, the task in hand is of critical importance for the choice of the appropriate display system, but currently I am unable to be more precise beyond indicating some factors influencing the choice.

Concluding, the results of this thesis are relevant for an industrial design engineer, both for the designing process itself and for the users of the products designed. Important considerations for choosing an appropriate way of providing a spatial impression of a

product or scene are the matching of the display to the task in hand, the disturbing effects of distortions, and the intuitiveness of the method of selecting a viewpoint.

Perceptual theories

This thesis has described some experiments in sparsely investigated areas. The compensatory effect of viewpoint multiplicity on image quality was tested. Furthermore the experiments dealt with perception and performance on technical tasks with a transparent scene. The results may give new grounds for judging and correcting theories concerning human information extraction from transparent scenes.

For an analysis of the spatial cues required for a task (see Chapter 2) the direct theory was found to be more useful than the indirect theory. The direct theory indicates that the question about the required information is urgent as it will drive the explorative behaviour of the observer, while the indirect theory places more interest on the extraction of 3D structure from the light from the environment.

The need for a complete reconstruction, as suggested by the indirect theory, is questionable. A complete reconstruction seems impossible given only some pixels in a view representing a wire. With normal baggage inspection, where only a single x-ray view is available, a reliable reconstruction can again not be made. However, these and the other tasks discussed in this thesis could be achieved with limited depth cues. As Tittle, Todd, Perotti and Norman (1995) suggested: "Most perceptual judgements required in natural vision do not require an explicit knowledge of Euclidean metric structure and can be performed accurately on the basis of ordinal or topological relations". Why should one check all cues if one of them is sufficient? Building a complete reconstruction of the scene is a waste of energy, and I suspect that humans only do things if they have a good reason (though not necessarily a logical reason) to do so.

On the other hand, the direct theory seems to oversimplify the extraction of information from the scene. Biological evidence indicates that neural cells in the eye do indeed extract zero-crossings from the light falling into the eye, as suggested by the indirect approach (see Figure 2.6). The direct theory does not explain why finding zero-crossings is essential for finding task-specific information. The suggestions of the direct approach, for the bump matching experiment described in Chapter 2, are an interesting example of such an oversimplification. The direct theory suggested that the width/height ratios of the bumps can be compared, but one needs the contours of the bumps to find the width and the height. In order to see these contours one needs motion parallax or texture cues.

Neither the direct nor the indirect theory explain *how* the task in hand steers exploratory behaviour. Knowledge about this relation is essential for building efficient interfaces and for understanding how spatial cues can be substituted for other spatial cues, in order to provide the observer with the information required for his task.