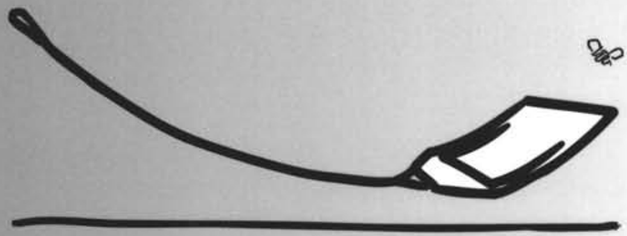
EWEP4

Fourth European Workshop on Ecological Psychology



Zeist, the Netherlands, July, 2-5 1996

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Introduction

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One of the enduring pleasures of the EWEP meetings is their eclecticism. They thrive on the juxtaposition of contrasting domains of perceptual/motor research, being either empirical investigations aimed at implementation or pure theoretical studies. This is again the case at this Fourth European Workshop on Ecological Psychology, organised conjointly by the Faculty of Industrial Design Engineering of Delft University of Technology and the Helmholtz Institute of Utrecht University.

Implementation of the Gibsonian theory of perception and action is found in the design of endoscopic instruments by multisiciplinary research teams where psychologists, mechanical engineers and surgeons collaborate. Two such teams decided to establish regular contact and to compare at this workshop their research results.

The two invited speakers, dr. A. van Doorn and dr. J. Todd probe some theoretical aspects of shape perception. Can the perception of tilt and slant, for instance, be considered as derived from a pictorial depth map, as most perceptual theories hold? Or is tilt and slant perception more precise than depth perception - as can be expected in the Gibsonian tradition?

Acknowledging perceptual/motor experience is an important factor in understanding and improving the design of industrial products. The perceptual studies presented here challenge us to raise new scientific questions but also and foremost, they should enable us to extend and sharpen our own perceptual/motor experiences.

Since this workshop is my *adieu* to the ecological community - as I am changing jobs - I would like to thank its members for their inspiration, by offering the attendants of this workshop a little gift. It is a small box demonstrating Land's colour theory. I chose it for three reasons:

(1) as an example of how empirical research can go together with sharpening colour experience itself;

(2) as an illustration of a design solution for a didactic problem: Land's demo has to be experienced. A verbal explanation is not convincing;

(3) as a reminder of the importance of looking for other theories besides Gibson's, that offer the same kind of functionality. Land as well as Gibson accentuates the perceptual functionality of structural invariants in the light pattern rather than the local characteristics of small light patches.

Symposium on Endoscopy

Human Performance in Minimally Invasive Surgery

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Abstract

This paper summarizes a program of research to examine human performance issues associated with minimally invasive surgery in general and laparoscopic cholecystectomy in particular. Two aspects of laparoscopic surgery were studied --- the conversion decision and perceptual-motor coordination. The conversion decision refers to the need to continuously monitor progress and to evaluate the relative benefits of continuing laparoscopically versus converting to a more invasive open surgical procedure. The perceptual-motor coordination problem refers to the requirement for the surgeon to adapt to the restricted visual information provided by the laparoscopic video display, to the restricted tactile information and movement allowed by the surgical instruments, and to the mapping between perception and action that results from the coupling between instruments and display.

Introduction

Advances in sensor and medical instrument technology have led to revolutionary changes in the way many surgical procedures are performed. Procedures that in the past have required large incisions through which surgeons could directly see and manipulate anatomical structures are now being performed through small incisions using fiber optic cameras and specially designed surgical instruments. These "minimally invasive" procedures offer great benefits to patients. For example, cholecystectomies which in the past required a week to ten days recovery in the hospital with up to a month before returning to work, now are routinely done with little more than a day in the hospital and 3-5 days to total recovery.

However, the advances for patients have been purchased at the price of increased demands on surgeons. The new layer of technology between surgeon and patient introduces new decisions, requires new patterns of perceptual-motor coordination, and in some cases increases the risk of catastrophic errors (e.g., cutting the common bile duct). In many ways, the technological revolution in surgery is a mirror of developments in other domains (e.g., aviation, manufacturing, and process control) --- the surgeon has become a "human factor" in a complex human-machine system. We have recently begun studying the human factors of laparoscopic cholecystectomy. We have focused on two aspects of this surgery --- the conversion decision and the perceptual-motor coordination problem.

The Conversion Decision

The term "conversion" refers to the critical decision point during which the surgeon realizes that further operative progression utilizing laparoscopic . . . maneuvering may not be appropriate because of temporal or physiologic considerations, or more commonly, because of anatomical limitations which make further endoscopic dissection potentially more risky. . . . The concept of "conversion" is truly interesting because of the psychological dynamics which are involved in the decision process. . . . The urge to follow through with an endoscopic approach may be so strong that judgment becomes clouded and the timing of the conversion process is, therefore, delayed until an untoward event has occurred (knowingly or unknowingly)! We all recognize that the oft-used phrase "to convert is not a complication, but represents good judgment' is indeed our standard, but in the "heat" of the O.R., some forget this admonition because of ego, machismo, or some other inherent intangible in the psyche. Greene (1995, p. 11)

After field observations, informal interviews, and knowledge audits with surgeons, we have chosen a formal interview procedure using video tapes from three "difficult" cases to better understand the conversion decision. Twenty interviews were conducted --- ten with staff surgeons with extensive experience with both open and laparoscopic surgery and ten with senior (4th & 5th year) surgical residents. The interviews include both direct, preplanned questions and open ended opportunities for the surgeons to make running commentary on the progress of the surgery. The preplanned questions included probes where the surgeons were asked to assess the probability that the surgery will be completed laparoscopically and to assess the skill level required for successful completion of the surgery. The running commentary allowed the surgeons to point out critical information for guiding their actions and decisions. The interviews have been transcribed and are being coded to allow for both qualitative and quantitative comparisons between the staff surgeons and the residents.

Preliminary qualitative analysis shows that there is consensus on some points, but disagreement on others with respect to the conversion decision. Many surgeons commented on time (i.e., the duration of surgery) as a critical factor in the conversion decision. In general, laparoscopic procedures take much more time than open procedures. Surgeons are often concerned about the consequences of the increased time that the patient spends under anesthesia. Some surgeons set strict limits on what they need to accomplish in a set period of time, others were more informal in their consideration of time. There seemed to be some disagreement about the issue of the patient's age (one of the cases involved an 80 year old woman). For some surgeons, age was a strong contra-indicator for laparoscopy. They had concern about the consequences of a prolonged procedure. Others thought that age was a major reason for laparoscopy, they tended to worry about the increased trauma of open procedures.

As in other studies of cognition in the "wild" (e.g., Amalberti & Deblon, 1992; Xiao, 1994) the metacognitive awareness of one's own limitations and the ability to anticipate and plan to avoid dangerous or demanding situations seems to be a very important component of expertise. As one staff surgeon commented, " a good surgeon believes what he sees, a poor surgeon sees what he believes." It seems that a cautious attitude and a healthy respect for potential errors helps to prevent experts from being led down garden paths to catastrophe.

Perceptual-Motor Coordination

As he poked at the tissue, trying to tease out recognizable structures, he had a little trouble using the remote-control forceps. Vessels kept slipping out of his instrument's grasp, falling out of sight. His frustration was obvious. As he had so many times before, he wanted to reach out, grasp the vessels between his fingers, and follow them to where they branched. But all there was to touch was the smooth glass of the video monitor. Finally, after several attempts, he isolated and clamped the cystic artery. It was ready to cut. Slowly, he moved the scalpel toward the artery, but just when it looked like the blade was going to make contact with the vessel, the blade passed behind it. Several times he pulled the blade back, adjusted its position, and tried to cut the artery, but the lack of depth perception prevented him from correctly judging the space. The scalpel repeatedly jabbed at nothing, first overshooting then undershooting its mark. Through three attempts the scalpel failed to connect. On the fourth, instead of empty space, the surgeon hit liver. Gaster (1993, p. 270).

The introduction of the fiber optic camera and the long, extended instruments that pivot at the ports of entry into the surgical space results in increased degrees of freedom to the problem of coordinating perception and action. In addition, valuable sources of information for managing the coordination, such as binocular cues to depth and tactile cues from directly touching the anatomy, are lost. A crude, but effective laboratory simulation has been designed to evaluate these increased perceptual-motor demands of minimally invasive surgery.

The simulation requires subjects to pick-up and move thin plastic chips from one vessel to another using laparoscopic instruments (Endo Babcocks). The movement requires that the chips be transferred between instruments in the left and right hands. Direct view of the workspace is occluded by a plywood barrier. Visual feedback is provided by a video camera (to the right or left of the workspace) and a video monitor positioned approximately at the subjects eyeheight directly above and behind the workspace. Rubber bands provide an elastic pivot point for the laparoscopic instruments as they pass through the plywood barrier.

A transfer of training paradigm is being used to evaluate critical dimensions of the perceptual-motor coordination. With this paradigm subjects are trained in a specific orientation (e.g., camera at the left hand; picking up chips near the camera and moving them from the left, transferring them to the right hand and depositing them in a vessel far from the camera) and then transferred to an alternative orientation (e.g., camera is repositioned to the right side, subject is moved to the reverse side of the workspace, or vessels are rearranged within the workspace). Are some rearrangements more difficult to adapt to than others? The differences in adaptation to rearrangement of the workspace allows inferences to be made about which dimensions are most critical to the coordination. Changes that led to difficulties were assumed to effect dimensions that are critical to the coordination. Changes that were easily adjusted to were assumed to effect dimensions that are less critical to the coordination. Preliminary analyses show that rearrangements that affected the dynamics of the perception-action coupling were most disruptive. Rearrangements that preserved the dynamic coupling resulted in less disruption.

Summary

The development of minimally invasive surgery is an important challenge to human factors and ecological psychology. It is an ongoing naturalistic experiment that provides a rich opportunity to study perception, cognition, and action in the wild. As a naturalistic experiment it will be a rich source of data and information that must be integrated into basic ecological theories of human performance. As an evolving technology that effects the life and well being of people throughout the world (e.g., over 600,000 cholecystectomies were performed in the US in 1991) it is an opportunity to translate basic research into creative engineering solutions (e.g., Smets, 1995). Gaster (1993) ends his compelling description of the difficulties that surgeons faced with this new technology with the question of whether the surgeon was "fit enough to make it up the slope of his next learning curve." The challenge for human factors and ecological psychology is whether our science is mature enough to stand with the medical community to harness this new technology.

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Man-Machine Aspects of Minimally Invasive Surgery

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Abstract

Minimally invasive surgery is a recent development in surgery with important consequences for the functioning of the surgeon. In this technique the view of the surgeon is based on a laparo- scope, a camera, presenting a 2-dimensional image of the operating field. The tactile observations and the perception of forces are obtained via the special tools devised for this type of surgery. A model of the surgeon in conventional open surgery and in minimally invasive surgery is generated to explain the consequences of the differences between the techniques.

Introduction

Important developments can be observed in surgery over the recent years of which the minimally invasive surgery or keyhole surgery is probably the most outstanding [Satava, 1993]. This type of surgery is based on the use of a limited number of feedthroughs, so-called trocars, applied, for instance, through the abdominal wall. Surgical tools are inserted through these trocars which have a diameter of 5 to 12 millimetres and in order to enable the surgeon to observe his actions, a small camera is introduced through one of the trocars. The video camera with fibre optics is called endoscope (internal scope) or laparoscope (lap scope). Owing to the prominent role of the camera the method is also referred to as endoscopic or laparoscopic surgery. The abdominal cavity is inflated using carbon dioxide, or mechanically expanded so that a working space is created in which to operate the surgical tools. Minimally invasive surgery in principle can be applied to any area of the body, including the abdomen (laparoscopy), chest (thorascopy), joints (arthroscopy), gastrointestinal tract (e.g. coloscopy of the colon) and blood vessels (angioscopy). As we are mainly concerned with the abdominal applications of the technique, most of the material presented herein will pertain to laparoscopy.

The minimally invasive surgical technique may have great benefits for the patient. The injuries of the abdominal wall are much less compared to conventional surgery, in which extensive incisions produce larger scars detrimental to the speed of recovery after the operation. Also, in principle, the risk of infections is smaller because of a virtually closed system. Finally there is the tendency to operate with higher accuracy due to the magnification by the camera. All these advantages for the patient have stimulated the development of this type of surgery, which has only been in use since 1989, when it really took off after the introduction of the CCD camera, the Charge Coupled Device semiconductor chip camera [Classen et al., 1987]. It was primarily the success of the laparoscopic removal of the gall bladder which contributed to this upward surge. That operation has now become generally accepted, reducing hospital stays from eight down to two days. The potential advantage of fast recovery of the patient has led to a strong increase of interest in recent years and new applications are reported continually [Boutin et al., 1991, Dallemagne et al., 1991, Jansen, 1994, White & White, 1989].

Minimally invasive surgery, however, is also characterised by the surgeon's lack of direct mechanical contact with the tissue to be operated upon and by the lack of direct view on the area of operation; the surgeon has to operate on the guidance of a video image. So, for the surgeon there are severe disadvantages involved with the application of this complicated technique [Herfarth et al., 1994]. Another consequence of the complexity of the procedure is that the quality and safety of the surgery depends even more than with conventional surgery on the skills of the individual surgeon. It can nevertheless be expected that this technique will continue to supplant conventional operations in the abdominal and thoracic cavity. With these new applications, however, the disadvantages of the technique are much more prominent than with the relatively simple gall bladder removal. The minimally invasive approach will have to be improved and the disadvantages be reduced to be able to extend the range of its surgical applications.

A surgeon's model

Open Surgery

In conventional or open surgery the procedure is characterised by a surgeon who invades the body with an incision through healthy tissue, which is made large enough to expose the organ to be operated upon to the surgeon's eyes and hands.

Perception. In open surgery there is a direct three-dimensional view on the operating field based on the binocular vision of the surgeon. Sometimes this view is impaired by a location deep in a cavity of the body or by small dimensions of the organs involved. Then assisting provisions like special illumination or microscopes for microsurgery are needed. There is, however, a large freedom to approach the organ in a versatile way for an optimal perception. This same freedom is present for the tactile observations of the surgeon. The surgeon is free to handle the organs with his hands only restricted by his glove. This way he can judge the condition of the tissues and feel the normalities and abnormalities in strength or consistency of tissues based on his experience. Recapitulating, the surgeon can use his senses, most importantly his view and tactile sense, in a nearly optimal way in accordance with his daily use of his senses.

Tools. During the open procedure the surgeon can use the whole realm of handhold surgical tools with the lancet as most important representative. Handheld tools are ergonomically well developed and provide mechanical information through force feedback of the interaction between the tissue and the tool. This is especially true when the surgeon uses his own hands as a tool for instance for stretching or separating tissue. Complex motions with the tools can be performed owing to the fully exposed operating field. Open surgery can thus be modelled by a feedback loop containing the surgeon with his senses, hands and tools. It can be noted that in open surgery the surgeon is working autonomously with only some additional handhold tools and perception aids.

Minimally Invasive Surgery

Minimally invasive surgery is characterised by the use of multiple small incisions producing minimal damage to healthy tissue of the patient. As a direct consequence the visibility and accessibility of the operating field are restricted and the organs are not freely exposed to the eyes and the hands of the surgeon. The sensing and actuator capabilities of the surgeon are thus severely restricted.

Perception. In minimally invasive surgery perception of the operating field is provided by a camera, an endoscope with illumination giving a two-dimensional view on a television screen in the operating theatre. Although magnification may enhance vision, the field of view and the restricted directing freedom in one of the trocars limit perception capabilities. The properties of the video signal like limited resolution, contrast and color fidelity present a further reduction of the vision of the surgeon [Tendick et al., 1993]. Additionally, in practice, the image quality is often impaired by contamination of the endoscope lens and by smoke produced by diathermy cutting. So the view on the operating field is significantly reduced by an image of limited quality, limited field of view and lack of disparity depth perception. The reduction of perception also pertains to the tactile sense. In minimally invasive surgery long tools of limited cross section are used and the surgeon is no longer capable of feeling by touching the organs with his hands. The internal friction caused by the elongated construction of the tools is considerable. Information on the consistency of the tissue passed through the instrument to the hands of the surgeon is therefore severely reduced. Another disturbing factor is the force needed to position the relatively heavy instruments with the unsupported arm and hand.

Tools. The surgical treatment is performed by the special endoscopic instruments with only four degrees of freedom because they have to pivot about the point of incision through the skin [Jansen, Cuesta, 1993, Melzer, 1992]. This gives an important reduction in manipulation capabilities relative to the human arm and hand with its redundant seven degrees of freedom which make alternatives for the same pose of the hand possible [Anderson, Romfh, 1980]. Due to the aforementioned internal friction of the tools and the relatively high positioning forces needed, the mechanical information of the interaction between the tissue and the tool by force feedback is also diminished. The capacity of the hand of the surgeon as a versatile tool is of course also lost. This all leads to a manipulation capability in minimally invasive surgery which is strongly restricted compared to conventional surgery due to a decreased freedom of motion and increased mass and internal friction of the endoscopic tools. The procedure of minimally invasive surgery can thus be modelled by a feedback loop containing the surgeon with his senses, hands and his tools, but now handicapped by limited vision and tactile perception and by tools of lower mechanical quality. It can be observed that now in the feedback loop some additional constraining mechanisms are in series with the senses and hands of the surgeon, hampering him to work as a craftsman. In addition, the surgeon is now dependent on another person handling the camera (assistant surgeon) for his vision. This, together with the elongated tools used, impairs the hand-eye coordination so important for the delicacy of the surgical actions.

Comparing Open and Minimally Invasive Surgery

When comparing minimally invasive surgery and conventional open surgery using both models it is noticed that both the sensing and the actuator capabilities of the surgeon are harmed by the minimally invasive technique. Consequently the surgeon is not helped at all by this technique and there is hardly any advantage indicated for the operation procedure itself. It is only the patient who reaps a benefit by reduced damage to his healthy tissues and a resulting fast recovery. It is important for the evolution of minimally invasive surgery that not only the drawbacks of the technique be reduced but also the technique be essentially improved to present some advantages to the surgeon and to the operation procedure as well to really become an attractive alternative for any surgeon.

Discussion

Minimally invasive surgery is characterised by a decreased capability of the surgeon to observe the tissue to be operated upon. The endoscope limits the vision of the surgeon, while his tactile information is lost and the interaction of the surgical tool with the tissue is obscured. Improvements to the minimally invasive technique will be directed to alleviating these restrictions. The most important limitations in the minimally invasive approach must be uncovered by analysing the role of these restrictions in clinical practice. To this end a recording and analysis method has been designed, which is used as a basic tool to define developments necessary to improve the quality and speed of the operation [Claus et al., 1995]. The same analysis method can also be used for defining improvements in conventional surgery or to make comparisons of conventional surgery with the minimally invasive approach. It is already clear that the development of new procedures and tools for endoscopy can also be beneficial for the advancement of conventional surgery.

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Direct perception in endoscopy

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Abstract

Laparoscopic surgery has great advantages for the patient. However, there appear to be no advantages for the surgeon. The direct contact between surgeon and patient is lost during laparoscopic operation. Both visual and haptic information are reduced compared to open surgery. The ecological, or direct perception theory (Gibson, 1979) relates information to action perception coupling. Action is a precondition for perception. A person who changes his viewpoint gets spatial information because of parallax shifts. Spatial information might also be obtained by changing the location of the light source because of the shifts in shadow. A surgeon who moves a laparoscopic manipulator will get information about the manipulator's orientation and location relative to the tissue. Information is obtained when a person perceives the results of own actions, when there is a coupling between action and perception.

A surgeon should be provided with possibilities to act, and information about these actions should be fed back to the surgeon. Laparoscopic scopes and instruments designed based on action possibilities and information feedback may restore the direct contact between surgeon and patient.

Introduction

Endoscopic operation has great advantages for the patient. The operation proceeds through small incisions (key-holes) which minimises the amount of healthy tissue being damaged. Because the incisions are small, de-hydration and risk of infections are reduced. Also the recovery period is reduced. For the surgeon however, there are only disadvantages (Grimbergen 1996). Because of the lack of direct contact, manipulation becomes difficult resulting in increased operation time. By loss of direct contact we not only mean the loss of tactile information, but also the reduction of visual information. The surgeon is provided with a 2D projection on a monitor screen, obtained using a rigid laparoscope.

Developments in the field of endoscopy seem to focus on two aspects, namely the implementation of binocular disparity (Griffin et al. 1995) and the implementation of force feedback to provide for tactile information. The later one is aimed at restoring the haptic array in order to provide information about the tissue, and the forces applied to it. This exceeds

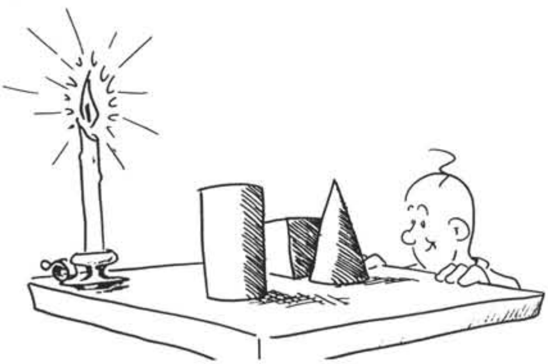

Figure 1: An observer, light source and environment.

the scope of this paper. The first one is aimed at solving problems resulting from a lack of depth perception. However, according to Gibson's ecological perception theory (Gibson, 1979), there is more to depth perception than binocularity. Classical approaches start from two 2D projections, Gibson assumes an array of information. Light structured by the environment is called an optic array.

The optic array holds three sources of information. First, because the part of the array which is being picked-up depends on the position of the observer, the optic array contains the observers viewpoint. Second, because the light is structured by the environment, the optic array contains the arrangement of the environment. Third, because light originates from a light source, the optic array provides the position of this light source. The relation between these three sources of information is schematically shown in Figure 1. An observer who has control over two of these three factors is able to obtain information about the third one. For example, an observer who changes his viewpoint, while he leaves the position of the light source unchanged, obtains information about the lay out of the environment. This information is obtained through a coupling between action and perception, through a coupling between proprioceptive and visual information. Proprioceptive information is used as a reference to visual information.

Apart from selecting a viewpoint, or relocating the light source, viewing one's actions within the environment assists depth information. A hand provides for a reference of size, whereas relocating an object supplies information about the distance towards that object. The importance of the relation between proprioceptive and visual information is shown when it is changed, for example by wearing coloured goggles making different colours appearing at different locations (Kohler, 1962). Observers need time to adapt to the new relation between proprioceptive, and extroceptive information. After this period of adaptation, all actions can be performed normally. This leads to the conclusion that not only being able to act within the environment, but especially the consistency of the coupling between proprioceptive and visual information is important.

In summary, the ability to act within the environment, and sensing these actions, thus a coupling between action and perception, makes depth perception possible. There are three sources of information which all should be focused on when improving depth perception for minimally invasive surgery. The manner in which this can be implemented is the focus of this paper.

Exploring the optic array: movement parallax

During current laparoscopic operations, the surgeon is hindered in explorative movements by the limited motions of the laparoscope. The laparoscope is rigid and because of the fixed position of the trocar, through which the laparoscope enters the abdomen, motions are restricted to a sphere (see Figure 2-A). Any point of interest can therefore only be approached from one direction, namely, along the straight line between the trocar and point of interest. These movements can be compared with examining a table from a distance. However, during exploration the point of interest preferably is approached from different angles, compared to examining the table by walking around it. Therefore, preferably, the

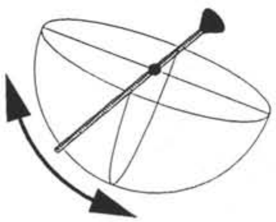

Figure 2A : Laparoscopic movements

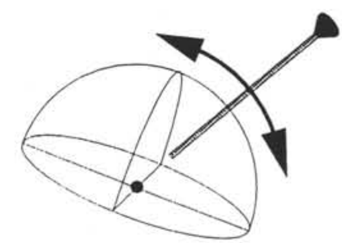

Figure 2B : Movements according to the Delft Virtual Window System

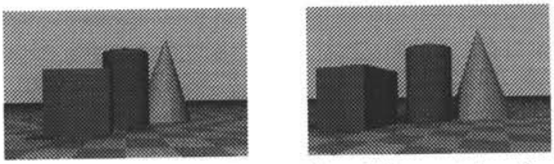

Figure 3: Moving the camera provides for parallax shifts, and therefore for depth information

centre of rotation is located at the point of interest (see Figure 2-B).

This problem might be solved using a laparoscope based on the Delft Virtual Window System (DVWS, Smets 1995). The DVWS, a system based on coupling action and perception, makes depth perception possible by means of a single monitor screen. A camera can rotate around a fixation point and is coupled to the head movements of an observer. Parallax shifts within the image increase with and thus indicate the distance towards the fixation point (see Figure 3). For the observer who is controlling the camera motions, sizes and distances are intuitively clear. Not only does a surgeon using a laparoscope based on the DVWS has the ability to explore and look around an object, also the control over the camera movements is partly restored. An laparoscope based on the DVWS allows him to explore by means of head movements. The selection of the fixation point is done by moving the entire laparoscope.

The advantage of a laparoscope based on the DVWS is the ability to explore. Main problems for implementation involve sterilisation and amount of camera motion. Sterilisation restricts the applicable mechanisms, and the amount of camera motions are restricted by the size of the mechanism, which has to be as small as possible.

Controlling the light: shadow movement parallax

The optic array reveals the position of the observer relative to the environment, but also the position of the light source. By adjusting the position of the light source, shadows and reflections will change accordingly. When an observer controls the motions of the light source, thus when there is an action perception coupling, the changes of the shadows provide information about the environment. Moving a light source might be implemented for endoscopy but has the same disadvantages as moving a camera. However, a moving light source can be simulated by two stationary light sources of which the intensity varies (Smets et al. 1995). A light source movement to the right is simulated by increasing the intensity of the right light source while simultaneously decreasing the left light source. For a light source movement to the left, the left intensity of the light source is increased while the intensity of the right light source is decreased. Advantage of this principle is that there are no moving parts required.

There are two ways in which the principle of shadow movement parallax can be applied to medical laparoscopy. First, the two light guides can be integrated within the laparoscope. Instead of one light guide, two guides are used, each of which connected to a separate light source. Second, the light sources can be integrated within the trocars. The distance between the light sources at the tip of the endoscope might be to small to have effect for a large distance towards the work area. Integration within the trocars does not have this problem, since the distance between trocars is large (approximate 30 cm).

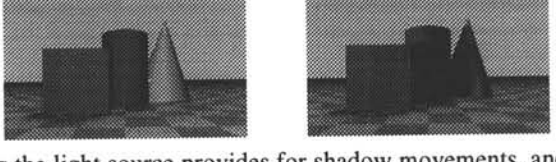

Figure 4: Moving the light source provides for shadow movements, and therefore for depth information

Manipulation within the environment

In the introduction it was stated that being able to act within and upon the environment supports depth perception. This can be seen during laparoscopic operation when surgeons apart from touching the tissue, move their manipulators to obtain depth information. The combination of proprioceptive and visual information provides a reference for sizes of, and distances towards objects.

Proprioceptive information enables manipulation without looking. The location and orientation of our hand are always known. The light switch in the bathroom can be found perfectly without looking. Laparoscopic manipulators lack proprioceptive feedback. While there is a vast amount of different manipulators, their interfaces (hand-held) are similar. Currently used manipulators mostly are based on a scissors-like interface. A surgeon cannot feel which manipulator he is using. Also, additional functionality of the manipulators, like the orientation of the manipulator's grab-end relative to the rest on the manipulator, is not fed back to the user. Since manipulation contributes to the perception of space, the interface of the manipulator seems important. During usage, not only the present state of the manipulator, but also which states can be reached from this point need to be communicated. Both how the grab-end is rotated and how far it can be continued rotate needs to be communicated. Because the current state is not communicated, the manipulator is moved in order to discover this. Improving the interface allows the surgeon to use the manipulator as a reference for his visual information, and therefore his perception of the environment.

Conclusions

In this paper we considered the importance of a coupling between action and perception for obtaining depth information during laparoscopic surgery. Starting from Gibson concept of optic array, there are three methods to obtain depth information: by changing viewpoint (viewpoint movement parallax), by changing the location or the intensity of the light source (shadow movement parallax), or by acting upon the environment.

A laparoscope based on the DVWS allows explorative movements by the surgeon. However, it requires a laparoscope with moving parts. Preferably, the amount of moving parts is minimised. Shadow movement parallax does not require moving parts. This simplifies implementation but also limits the explorative movements of the surgeon. Experiments will have to show whether shadow movement parallax is feasible for explorative tasks by minimal invasive surgery. Apart from improving the surgeons visual information, the interface of the manipulators need also to be considered. Increasing the perceivability of the manipulator's functions will make better use of the ability to feel our actions, and therefore improve depth perception.

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Workshop

Visual Control of Balance during Walking: Model and Data

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Abstract

Three experiments tested the hypothesis that postural sway during locomotion is visually regulated by motion parallax as well as optical expansion. Oscillating displays of 3D scenes were presented to participants walking on a treadmill, while postural sway was recorded. Displays simulated (a) a cloud, in which parallax and expansion are congruent, (b) a hallway, (c) the side walls of the hallway, (d) a ground surface, (e) a wall, (f) the wall with a central hole, (g) a hall farther from the observer, and (h) a wall farther from the observer. Responses with the cloud were isotropic and directionally specific. The other displays demonstrated that motion parallax was more effective than simple horizontal flow in eliciting lateral sway. These results are consistent with the hypothesis that adaptive control of sway during walking is based on congruent expansion and parallax in natural environments.

Introduction

To maintain balance during locomotion, humans and other animals must make functionally specific postural adjustments, that is, of a direction, amplitude, and type appropriate to the postural disturbance. Optic flow at the eye of a swaying observer contains information that specifies these aspects of the required adjustments. Body sway generates a global flow field, illustrated in Figure 1, containing (a) a focus of expansion in the direction of sway (diverging arrows), and (b) a pattern of motion parallax that increases from zero in the direction of sway to a maximum in the perpendicular direction (parallel arrows), which also depends on depth structure. In a stochastic 3D environment, expansion and parallax congruently specify self-motion, and minimizing them would yield compensatory sway with an appropriate direction and amplitude. This theory has several advantages for adaptive balance control: (1) information is available in any visual direction, (2) information about the distance of objects is not required, and (3) it applies to both standing and walking, which simply adds a constant velocity motion to the flow field. On the other hand, in certain environments such as a hallway, truncated depth produces a skewed parallax pattern, yielding some biases (Warren, Kay, & Yilmaz, in press).

The present experiments test the hypothesis that motion parallax is used to regulate postural sway during walking. In a stochastic 3D environment, expansion and parallax are congruent, and the theory thus predicts that postural sway should be directionally specific and isotropic. In Experiment 1, we tested this prediction using open-loop displays of an oscillating 3D cloud of squares. In Experiments 2 and 3, we tested the efficacy of motion parallax against simple horizontal flow.

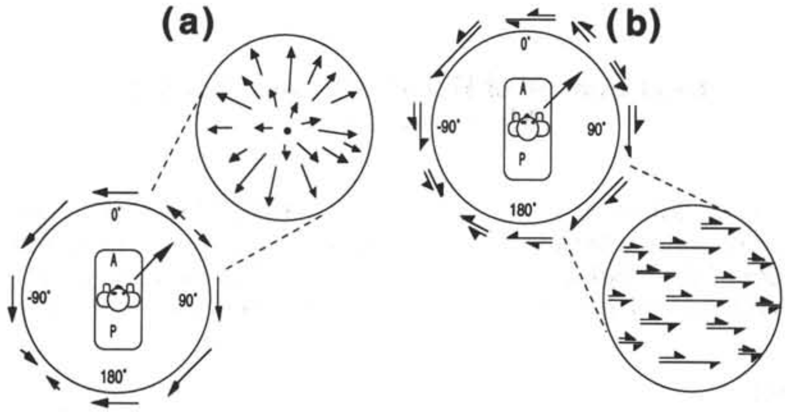

Figure 1. Schematic of optic flow field for a swaying observer. **(a)** Expansion: The focus of expansion lies in the direction of sway, grading into lamellar flow in the orthogonal direction. **(b)** Parallax: Differential motion is zero in the direction of sway, and maximal in the orthogonal direction.

Method

The displays were generated on a Silicon Graphics workstation and presented with a Barco video projector on a rear-projection screen centered in front of a moving treadmill (1 m/s). Displays simulated (a) a cloud, in which parallax and expansion are congruent, (b) a hallway, (c) the side walls of the hallway, (d) a ground surface, (e) a wall, (f) the wall with a central hole, (g) a hall farther from the observer, and (h) a wall farther from the observer. Two amplitudes (A = 0.2 e, 0.4 e peak-to-peak, where 1 e = 1.60 m) and three directions ($\alpha = 0°, 30°, 90°$, where 0° is straight ahead) of oscillation were tested in Experiment 1. In Experiments 2 and 3, one amplitude (.4 e) and one direction (90°) were used, and the fastest horizontal flow in the nearest region of the screen were equated between displays. Seven subjects participated in Experiment 1, eight in Experiment 2, and 9 in Experiment 3. They were instructed to stay oriented to the displays. Motion of a marker on the neck was used to determine the direction and amplitude of body sway. Marker position was recorded with a two-camera ELITE system at a sampling rate of 100 Hz. The mean direction of sway, mean peak-to-peak amplitude in that direction, phase of sway with respect to the driver, and correlation with the driver were determined by fitting the time series for each trial with a sinusoidal function at the driver frequency (see Warren et al., in press, for details of the method). Circular statistics were used in the analysis.

Results

Every participant exhibited reliable postural responses in experimental trials, with significant cross-correlations between driver and sway with all displays.

In Experiment 1 (cloud display), responses were both directionally specific and isotropic in amplitude (Figure 2). For each driver, sway was significantly clustered around a mean direction, with Raleigh tests yielding $r = 0.98$, $r = 0.95$, $r = 0.98$ for 0°, 30°, and 90° respectively ($N = 48$; $p < .001$). Hence, as is evident in Figure 2, compensatory sway corresponded closely to the specified direction. Responses were also isotropic. Mean sway amplitudes were 13.23 cm ($SD = 8.5$), 11.17 cm ($SD = 5.53$) and 12.26 cm ($SD = 6.6$) for the 0°, 30°, and 90° driver, respectively, $F(2, 12) = .15$, *ns*. Thus, sway amplitude did not depend on driver direction.

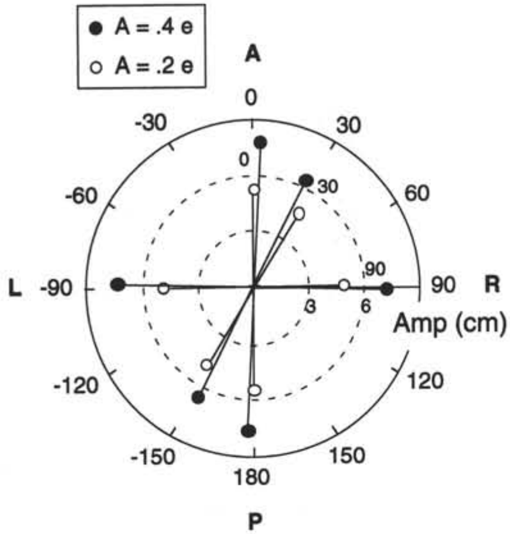

Figure 2. Polar plot of mean sway amplitude as a function of mean sway direction for the 0°, 30°, 90° drivers in Experiment 1 (cloud display).

Results of Experiment 2 are presented in Figure 3. First, both the Hole and the Floor displays induced lower amplitudes of sway than the Hall, indicating that, when horizontal motion is equated in the same region of the display, parallax present in the hallway induces a much greater response than the horizontal flow alone, consistent with the theory. Second, although there was a similar difference between the Hall and the Wall in the predicted direction, it failed to reach significance. We believe that this is due to the fact that, by equating the horizontal motion of the entire Wall to the hallway's fastest elements, we created an average screen velocity that was three times higher than in the hallway. This may have induced a large response without motion parallax, but it still remained less than the hallway display. We return to this issue in Experiment 3. Third, the significant difference between the Floor and the Hall rules out the hypothesis that observers maintain their position in the hallway by following a path of elements on the floor. On the other hand, the fact that the Side Walls condition was comparable to the Hall but significantly greater than the Floor strongly suggests that observers rely on the parallax of the side walls rather than the parallax of the floor.

In Experiment 3, the salient result is that the amplitude of sway is much greater with the Hall (M = 14.05 cm, SD = 3.20) than the Wall (M = 5.77 cm, SD = 2.19), $F(1, 7) = 10.43$, $p < .05$. Thus, when the mean horizontal velocity is comparable, the Hall elicits much greater sway than the full Wall. This is consistent with the hypothesis that motion parallax is more effective than horizontal flow in eliciting postural sway during walking.

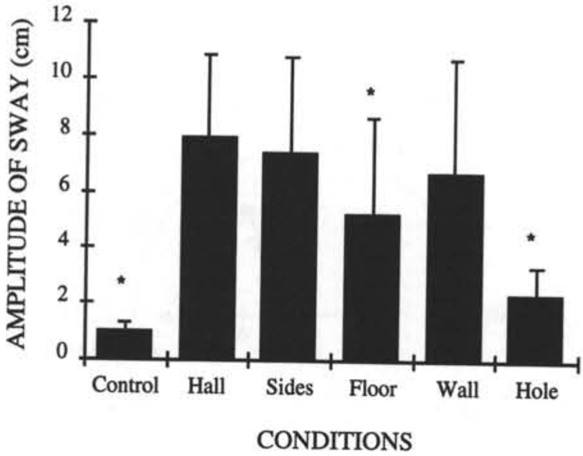

Figure 3. Mean sway amplitude and standard deviation for each display in Experiment 2. Driver amplitude = .4 e; driver frequency = .25 Hz. * indicates a significant ($p < .05$) difference between the display tested and the other displays.

Conclusion

The present experiments were designed to investigate the informational basis for the regulation of balance by testing the hypothesis that both motion parallax and optical expansion are used to control postural sway during walking. The results support this hypothesis. In Experiment 1, postural responses to an oscillating 3D cloud, in which expansion and parallax are congruent, were shown to be functionally specific. By manipulating the geometry of the visual scene in Experiments 2 and 3, we were able to show that motion parallax was more effective than horizontal flow in controlling sway. Thus, posture appears to be regulated by independent responses to radial expansion and motion parallax. This is precisely what one might expect from a robust visual control system, on several counts. First, the two variables are complementary, such that the focus of expansion lies in the direction of sway, whereas parallax is greatest in the perpendicular direction. Thus, posture can be adequately stabilized using information in any visual direction. Second, unlike simple horizontal motion, parallax is invariant under rotation. Third, visual thresholds for relative motion are lower than those for simple motion. Finally, the theory applies to the control of both standing posture and posture during locomotion, allowing for a constant velocity component corresponding to forward progression.

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How the Arm Can Influence What We See

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Abstract

We show that kinesthetic information concerning the posture and movement of the arm can influence the visually perceived size of an object.

Introduction

If we hold an object in our hand, we can both see and feel how large it is. Similarly we can both see and feel its position. Visually and tactually perceived sizes are known to interact (Rock and Harris, 1967), as are visually and tactually perceived positions (Rock and Harris, 1967; Welch and Warren, 1986) and visually perceived size and position (Gogel, 1990). In the present study we examine whether visual judgements of *size* are influenced by kinesthetic information concerning the object's *position*. Does information about the posture and the movements of the arm and hand with which one is holding an object influence the object's perceived size?

Methods

Subjects were given a 5 cm cube that they were asked to look at before the experiment started, and to hold under the table in their left hand during the experiment. In their right hand, they held a rod attached to a similar cube. They held this cube behind a mirror (see inset in figure 1). A visual simulation of a cube was presented through the mirror at the precise position at which they held the cube attached to the rod, 25 mm closer to themselves, or 25 mm further away. The simulated cube always had the same orientation as the one in their hand, but its size was varied between trials. The simulation was presented binocularly at a rate of 60 Hz per eye (taking account of the positions of the eyes and of the cube, and of the orientation of the latter, with a delay of less than 50 ms).

Subjects were not allowed to hold the cube itself in their right hand, because doing so would lead to conflicts between vision and touch whenever the simulated cube was larger or smaller than 5 cm, and would confront the subjects with the peculiar sensation of seeing the cube "through" their hand. Each presentation started with 7 seconds during which the subjects were free to move the cube in their right hand, and thereby also the visible cube, around as they liked. After that, they had to indicate whether the cube they had seen (and moved around) was larger, the same, or smaller than the one in their left hand.

A measure of response frequency was calculated for each of the 6 subjects, 9 sizes of the simulated cube, and 3 spatial relationships between the real and simulated cubes. This measure was:

$$\text{response frequency} = \frac{L-S}{L+E+S}$$

Where L, E and S are the number of times the subject responded "larger", "equal" and

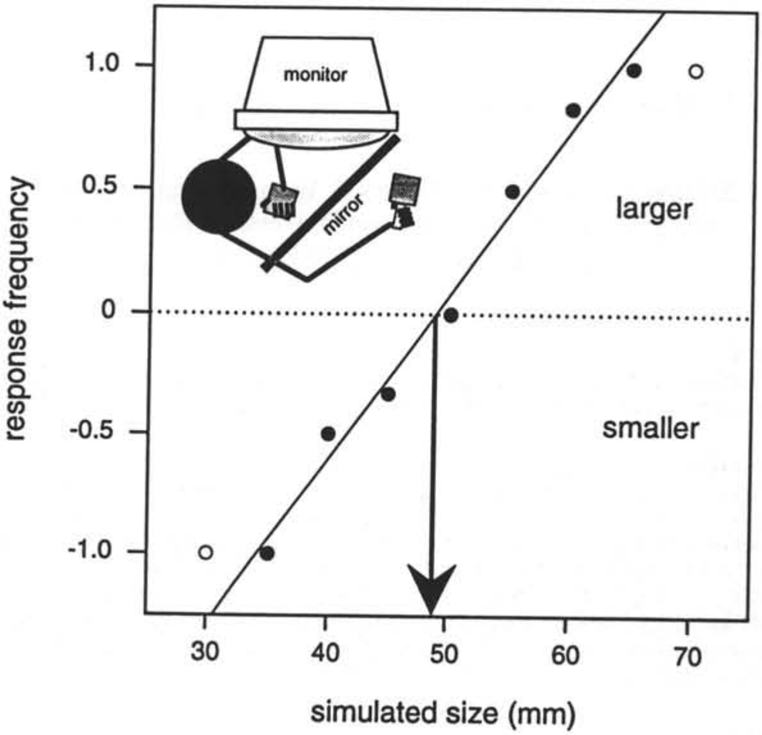

Figure 1 Sample data for one subject and condition

"smaller" respectively (each value was based on 6 presentations). From these values we estimated the size that matched the reference: the size of the simulated cube at which a linear fit to the relevant part of the data intersects the response frequency of zero. The relevant part of the data was defined as the section between the minimal and maximal obtained values of response frequency, including each of these values once. An example is shown in figure 1. The filled symbols show the values used for the fit. The arrow indicates the matching size.

Results and conclusions

Figure 2 shows the average matched size for all six subjects (± one standard error). The mismatch between the distance at which the cube was held and the simulated distance clearly influenced the perceived size. The influence was consistent with the visible cube being considered to be where it was held. When the cube was simulated 25 mm nearer than it was held, it was considered to be further away than the simulation, and thus to be larger (the same retinal size corresponds with a larger actual size if the object is further away). This is a strong effect: for a viewing distance of about 45 cm one would expect a change of about 3 mm at most in each direction, which is close to the values we find in figure 2. Thus, the kinesthetic information appears to be stronger than the conflicting visual information on distance.

As is evident from the standard errors, individual subjects made large systematic errors. Nevertheless, all subjects were very consistent in their judgements. As a

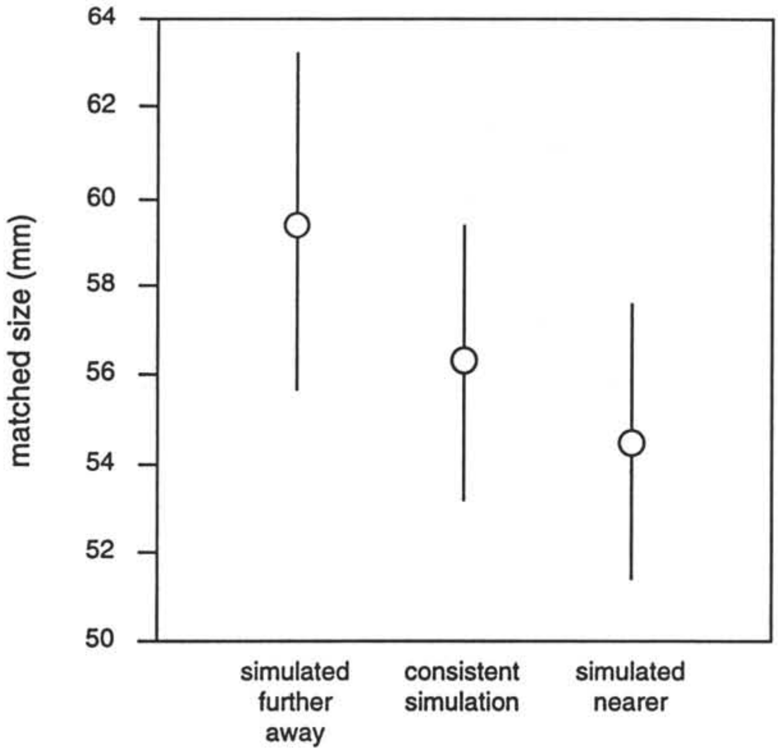

Figure 2 The average simulated size that matched the reference in the three conditions (±1SEM)

consequence, the differences between the three conditions were all significant ($p<0.05$) when tested with paired t-tests.

These results suggest that whereas vision dominates over touch for the perceived size of an object at a known distance (Rock and Harris, 1967), kinesthetic information from the arm (be it proprioception or efference copy, position or motion) dominates over information from the eyes when providing the information on distance that is required for interpreting retinal image size in terms of object size. However, there is an alternative explanation.

To ensure that subjects had optimal visual and kinesthetic information, we allowed them to move the rod around as they liked. Both vision and touch can benefit from such active, dynamic presentation (e.g. Burton, Turvey and Solomon, 1990; Johnston, Cumming and Landy, 1994; Oosterhoff, van Damme and van de Grind, 1993). This yields optimal stimuli, but the equivalence between the visual depth information in the different conditions is lost. Most importantly, unless subjects compensate for the 25 mm offsets in the positions of the simulated cube by holding the real cube nearer or further away, the simulated cube will - on average - be closer to or further from the subject on such trials. Although we tried to mask this effect by explicitly encouraging subjects to move the cube in depth, we cannot entirely exclude the possibility that failing to compensate for differences in the average distance to the simulated cube accounts for our results.

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Tool Use Learning : What does Expertise Mean ?
The Case of Stone Knapping in India

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Abstract

The aim of this study is to propound a way to define dexterity related to a complex motor skill, stone knapping, as it is still performed in India. An experimental field study has been carried out with craftsmen of two different levels of expertise.

Three levels of action have been worked on, the elementary functional action, the subgoal and the overall organisation of the task at hand. Results suggest that the expertise refers not to the overall organisation of the task but to the elementary level of action and to the dynamics of the succession of elementary movements to carry out a subgoal.

Introduction

What are the processes underlying the learning of complex skills which require, to reach a reasonable level of dexterity, not hundreds but thousands of trials over several years ? This question is seldom debated in studies on motor learning. Apart from sport, complex motor skills outside the laboratory have seldom been addressed by motor researches. The research presented appears as a plea for such studies. The skill studied here is *stone knapping*. It refers to a skill which is over two millions years old, specific of mankind and which is of great interest in the debate of hominization especially from an archaeological point of view.

In the present study we set up the following question : Is it possible to define the level of dexterity of a stone knapper and to study the learning process of such a skill ? To study this question we developed what we call "experimental field" studies based on the two following principles. First the craftsmen should be in a situation as close as possible to their everyday activity. Second, the data obtained should allow for analysis of parameters usually studied in laboratory experimental situations.

This perspective is becoming actually possible owing to the technological advances that allows for portable technological devices based on laboratory techniques. It rises new questions about how fundamental mechanisms studied in laboratory setting are used in functional complex motor skills. It is time now to go outside the laboratory and to study real life skills.

Purpose of the study

The aim of this study is to propose a way to define "dexterity" (Berstein, 1996) for complex motor skills. Based on an experimental study of stone knappers craftsmen in Khambhat (India), we shall develop the idea that when complex functional motor skills are concerned it is necessary to consider 1/ different levels of action organisation (plan of action, subgoal, elementary action); 2/ the movement relatively to the dynamical properties of the task at hand.

Three levels of action are referred to :

- Level 1. The *elementary functional actions*, which are the smallest unit of movement.

- Level 2. The *subgoals*, concern the way elementary actions are joined together.

- Level 3. The action, that is the *overall organisation of the task*, that is, how subgoals are sequenced to perform the task at hand.

Why stone knapping ?

The present study is issued of a collaboration with archaeologists. In archaeology, the study of skills involved in stone knapping is not anecdotal. It enables prehistorians to tackle major issues such as the specificity of the first human primates compared to the non–human primates, the emergence of socio–economically specialised tasks or else the factors responsible for technical changes.

Ethnographic data

Socio–economic context

In Khambhat (India) the bead industry is in the hand of two types of workshops depending on the quality of the products :

- Group 1, produces high quality beads, apprenticeships last about 7 to 10 years and are considered in the present study as experts (dextrous).

- Group 2, produces inferior quality beads, training lasts about 2 to 3 years, and are considered in the study as non–experts.

Description of the technique

The knapping technique is an "indirect percussion by rebound" (Pelegrin, 1994). The purpose of the action is to make a bead of a particular shape (spherical, cylindrical, etc.) from a piece of stone. The knapper uses two tools jointly :

- a sharp–pointed iron bar about fifty centimetres long, and two centimetres thick, stuck obliquely into the ground in front of the knapper;

- a buffalo horn hammer mounted on a thin wooden stick.

To detach a flake, the piece to be knapped is held between the fingers, and the edge of the piece applies against the extremity of the iron bar; the hammer, held in the other hand, strikes the piece to detach a flake from the point of contact with the iron bar.

Method of knapping

Knapping a bead is a two staged–process: a *rough–out* is first knapped from a piece of raw material, and then a *preform* is knapped from the rough–out. Our study deals with the second stage, knapping a preform from a rough–out.

The task is organised as a sequence of subgoals in order to obtain a good quality bead of a particular shape. For example, to knap a cylindrical bead , start with a parallepipedic rough–out with four crests, then apply the following sequence of actions or subgoals : calibration of the crest, end preparation, fluting (axial detachment of part or whole crest from one end), reduction of the crest by very short transversal flakes, end finishing.

The experiment

The experiment was based on the introduction of new situations for the craftsmen. They had to transfer their knowledge to new raw material (glass) and to the knapping of shape unknown, or at least unusual for them The hypothesis was the following : the capacity for the subjects to transfer their knapping knowledge to new raw material and new shapes indexes the level of dexterity; the study of the skills in two groups of 6 craftsmen whose length of apprenticeship differs from 3 years to 7 years will give us information on the learning process.

Experimental task

Each subject had to knap 10 beads in two raw materials (stone and glass) and of two different shapes (small cylindrical bead, large cylindrical bead).

Recording devices

A video camera (50 frames/s). An uniaxial accelerometer stuck on the non used pen of the hammer, connected to a portable computer Toshiba 600, via an ADC (sampling frequency 200 hz).

Results and discussion

Apart from the analysis of the finished product (the beads) (Roux, Bril & Dietrich, 1995), the three levels of the action has been analysed, the overall organisation of the knapping in subgoals, the dynamics of a succession of elementary movements to carry out a subgoal and the elementary movement of percussion .

The results show that, the overall organisation of the task does not differentiate the experts from the non experts. The important intra–individual variability for subjects of both groups, suggests the absence of plan–as–program (Agri & Chapman, 1991). Subjects use plans as resources. They improvise at any time according to possibilities afforded by the contingencies and constraints of the environment.

The analysis of the sequences of percussions was done owing to power spectral density and harmonic analysis of the acceleration of the hammer throughout the making of the bead. Results show greater variability and greater range of frequencies across trials for non–expert subjects. This suggests that experts are able of a greater stability corresponding to the capability to minimise the necessary energy for the task.

Results concerning the elementary action reveals very important differences in between the two groups. The analysis of the acceleration displayed during the movements of percussion of the hammer on the stone shows that the less skilled craftsmen display either too high or too small acceleration just prior to the stroke. Furthermore, expert subjects are able to adapt the acceleration very precisely to the raw material and to the size of the rough–out.

From the analysis of the overall strategy (or action plan), it appears that the subjects from both groups are able to organise their action plan in approximately the same way.

We come to the conclusion that the strategies observed depend to a large extent on the control of the elementary movement. While all subjects know about the necessary succession of subgoals, the higher control of the elementary movement lead to a minimalist overall task as it is the case for the more dextrous craftsmen. On the contrary, failures resulting from inadequate control of the elementary movement , as for less skilled subjects, lead to a more complex continuous decision–making process so as to reorganise the course of action according to the inadequate changes in the local situation. In this case, we come to the paradox of a more difficult planning activity for less skilled subjects.

To conclude, we hypothesize here that once a subject knows the necessary succession of subgoals needed to knap a bead of a given shape, the more important is to learn to generate the right forces to detach an adequate flake depending of the subgoal at hand. This necessitates the comprehension of the "affordances" of the task (including tools, raw material and action of the tool on the raw material), and the capabilities to use those affordances (Gibson, 1979). What must be learnt is not the movement per se which is quite simple, but the optimal adaptation to the environment.

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Putative Neurological Mechanisms in Catching: A Dual Task Approach

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Abstract

There is much debate on how an observer intercepts an approaching object. The present paper does not espouse any particular hypothesis but attempts to investigate the possible neurophysiological mechanisms involved in time to collision (ttc) computations. Subjects were required to respond to apparent movements presented in either temporal or nasal hemifields while attempting a ball catch. A temporal field advantage in reaction times to apparent motion stimuli under dual task conditions implicates midbrain structures in the perception of object motion, & possibly ttc computations. Additionally the prospect that ttc computations can become informationally encapsulated was investigated. In terms of their responses to apparent movement stimuli, no difference in performance between experienced interceptive sports participants & experienced non interceptive sports participants was observed. Video analysis of catching performance is ongoing.

Introduction

It is thought that input from the monocular temporal field has a more direct input to midbrain structures than does information originating from the monocular nasal field (Williams, Azzopardi, Cowey, 1995; Rafal, Henik & Smith, 1991). Indeed temporal field advantages have been observed in a phenomenon known as Inhibition of Return (IOR), which is said to reflect a preference for orienting to novel locations (Posner & Cohen, 1984; Posner, Rafal, Choate & Vaughan, 1985). More recently it has been demonstrated that IOR can be demonstrated for objects. Crucially these experiments involved objects in motion (Tipper et al., 1994). Thus it is possible that the same extrageniculate pathways implicated in IOR may also be involved in the processing of object motion, & even ttc computations.

Frost et al. (1990), suggest that a structure in the avian brain which is equivalent to the human midbrain structure, the Pulvinar, may be implicated in the detection of object motion, whilst being insensitive to optic flow information resulting from observer motion. These same authors proposed that that these structures are involved in the perception of looming stimuli. The pulvinar, which has direct connections with the basal ganglia & cerebellum, may also be involved in visual salience & the programming of finely tuned actions (Robinson & Petersen, 1992; Magariños-Ascone et al., 1988).

In a series of ongoing experiments, Corban & Eves (1995) have shown that a temporal field advantage exists in simple reaction times to apparent movement stimuli. However, under dual task conditions requiring a response to apparent movement & an additional catching task (a task assumed to require perception with a concomitant processing of object motion), this hemifield difference was not definitive & was dependent upon other factors. For example, subjects could be identified as belonging to one of two responder types: Those that could perform the two tasks simultaneously ('early responders') & those that could not respond to the apparent movements until after completing the catch ('late responders'). In a control condition where subjects were required to respond to the apparent movement only, both groups demonstrated a temporal field advantage. Under dual task conditions however, this temporal field advantage was not evident in either group, and there was a tendency for the effect to be reversed in the late responder subjects. The overall findings implicated midbrain structures in catching due to the observed structural interference. However insufficient sample size & lack of background information precluded any conclusions regarding why subjects 'fell' into two distinctly different groups. It may be however that those individuals identified as early responders posses some form of information encapsulation (Mcleod et al., 1986) for general ttc computations, & thus the amount of structural interference is reduced. It is also possible that these structures are involved in the programming of some aspect of the motor response required to intercept objects which could have resulted in the observed structural interference.

The present study sets out to examine these possibilities: That midbrain structures are involved in processing object motion & also in the production, or control, of actions associated with the perception of object motion. Additionally, is it the case that people who have experience in ttc situations (i.e., expert interceptive sports participants) posses a form of information encapsulation for ttc computations, and thus show no (or a reduced level) of structural interference under dual task conditions.

Method

Subjects consisted of equal numbers of male & female, interceptive & non interceptive sports performers. Sports were considered interceptive if they required participants to respond to moving projectiles. Thus included such sports as hockey, tennis, squash, rugby & football. Whereas examples of non interceptive sports included swimming, aerobics, dance & weightlifting. All subjects had participated at county level or higher in their particular sport. Each participated under two conditions: A control condition where subjects were required only to respond to apparent movements presented in either the temporal or nasal monocular hemifield; and a dual task condition where the additional secondary task was catching. Measures of subject's performance included reaction times to the apparent movements, as well as video taping of each session so as to asses different aspects of catching performance at a later date.

Results

Analysis thus far has focused on subject's reaction times to the apparent movements. These analysis yield a significant main effect of Field, $F_{(1,21)} = 6.29$, $p < 0.05$, with reaction time latencies shorter for temporal field apparent movements than those presented in the nasal field. In addition subjects responded quicker in the control condition compared to the catch (dual task) condition, $F_{(1,21)} = 110.67$, $p < 0.01$, (see Table 1 below). However there was no main effect of sporting experience (interceptive vs. non-interceptive), nor an interaction with this factor with any other factor. (all $p > 0.1$)

Video analysis of subject's catching performance & accuracy of responses to the apparent movements is currently in progress.

<u>Table 1:</u> Showing mean median reaction times (in milliseconds) for the main effects of condition and field respectively

Condition		Visual Field	
Control	Catch	Temporal	Nasal
315 msecs	445 msecs	374 msecs	385 msecs

Discussion

The above results add support to the hypothesis that information about object motion may be processed by extrageniculate pathways, due to the finding that response latencies to apparent movements were shorter in the temporal hemifield compared to the nasal hemifield. Also there is evidence of competition for neural resources, under dual task conditions, suggesting that some part of the ball catching task is utilising the same extrageniculate pathways. The subsequent video analysis of subject's catching performance may go some way to establishing under what conditions & which part of the catching task is competing for these neural resources.

Moreover, analysis of these data suggests that if midbrain structures are involved in ttc computations required by actions such as catching, then it is a hard wired system, & not the result of specific prior experience leading to some sort of information encapsulation.

In summary no firm conclusions can be drawn at this point , however initial analysis has provided some evidence to suggest ttc may be carried out by midbrain structures.

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Contributions of Peripheral and Central Vision to Stride Length Regulation in Long Jumping

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Abstract

This study investigated the effects of elimination of peripheral and central vision on performance in 14 long-jumpers. Full vision was compared with removal of central vision (missing field size of 53.1°) or removal of peripheral vision (field size restricted to 25.3° of central vision). Subjects completed nine jumps with three under each condition. Both the distance jumped and the stride pattern for the last 15 strides of the approach to the board were analysed. Subjects showed a reduction in the distance jumped without peripheral vision, confirming previous work (Eves, 1995). In addition, the data suggested a reduced variability in stride length occurred without peripheral vision. These data suggest that long jumpers may use peripheral vision to regulate their approach to the take-off board.

Introduction

Studies of movement perception have clearly demonstrated that peripheral vision was important in the perception of self-motion (Brandt & Dichgans, 1978). More recently, Andersen (1986) emphasised that information from central vision can also affect the perception of self-motion. Hence it appears that both peripheral and central vision may be relevant. Few studies however have investigated the possible contribution of central and peripheral vision to sporting performance. An early summary article of Russian research outlined the deleterious effects that elimination of peripheral vision had on a range of sports, e.g. javelin throwing and figure skating (Graybiel, Jokl & Trapp, 1955). Furthermore reductions in performance were more marked than those observed following loss of central vision. More recently, Eves (1995) demonstrated that the greatest reduction in the distance jumped for the long jump followed loss of peripheral vision.

This study represents a further investigation of the use of peripheral and central vision while long jumping. Evidence already exists for the use of optic flow variables to regulate stride length during the approach to the board in long jumping (Lee, Lishman & Thomson,1982; Berg, Wade & Greer, 1994). In this study, stride length regulation was investigated for full vision and with restriction of vision to either the peripheral or the central visual fields.

Methodology

Six female and eight male sport science students aged between 19 and 20 years performed nine jumps, three under each condition. None of the subjects were specialist long jumpers. Lightweight goggles were employed for restriction of visual input. Elimination of peripheral vision was achieved with 3.6 cm diameter tubes attached to the goggles so that the end of the tube was on average 8 cm from the pupil (field size of 25.3 ° of central vision). For elimination of central vision, a black, circular spot 1.9 cm in diameter was positioned on a pair of clear goggles on average 2 cm from the pupil. This results in removal of central vision (missing field size of 53.1°).

For the first triad of jumps, one was performed under each visual condition. Subjects were randomly allocated to the order in which visual conditions would be undertaken in the first triad. Subsequent triads followed the order of the first. Subjects jumped off a 15-20 stride run-up. Unlike competition, distance for each jump was measured from the front of the take-off foot rather than the front of the board with the distance measured in meters.

To assess stride length regulation, each approach run-up was recorded on two Panasonic F15 cameras linked to Panasonic NVFS88B recorders positioned so that each camera covered a 16 meter field of view which overlapped in the centre of the run-up. The final 15 strides of each run-up were digitised at 50 Hz using a PEAK5.0 digitising system. Camera calibration and point reconstruction was performed using a two dimensional version of the direct linear transformation (Abdel-Aziz & Karara, 1971) which effectively allows points to be measured in a defined plane, in this case the long jump run-up. Digitisation has been completed for six subjects so far.

For analysis of the distance jumped, a repeated ANOVA was employed with two within subject factors of **Condition** and **Jump**. For analyses involving stride length, a further within subject factor of **Step** was included. The Huynh-Feldt corrected probability was employed to control for violations of the sphericity assumption.

Results

Analysis of the distanced jumped revealed a main effect of **Condition** ($F(2,26)=13.11$ $p<0.001$), an effect for **Jump** which approached significance ($F(2,26)=3.03$ $p=0.066$) but no interaction between the two ($F(4,52)=0.38$ $p=0.825$). Further analyses of the **Condition** effect with the Newman-Keuls test ($p<0.05$) revealed that without peripheral vision subjects produced a shorter jump (mean=3.88 metres) than for subjects without central vision (mean=4.06 metres) and with full vision (mean=4.10 metres).

Analyses of stride pattern revealed an increase in length as subjects approached the take-off board (**Step**: $F(14,70)=7.01$ $p=0.002$) but no effect of either **Condition** ($F(2,10)=1.07$ $p=0.36$) or **Jump** ($F(2,10)=2.96$ $p=0.103$). Analysis of the variability of stride lengths also indicated a change over **Step** ($F(14,70)=3.69$ $p=0.017$). In addition, there was a marginally significant effect of **Condition** ($F(2,10)=3.86$ $p=0.057$) which suggested less variability without peripheral vision (mean=0.21) than either without central vision (mean=0.31) or with full vision (mean=0.34).

Discussion

These data extend the results of the previous study (Eves, 1995). Once again, absence of peripheral vision reduced the distance jumped in the long jump. Analyses of the stride pattern suggested this reduced distance was associated with a decrease in the variability of stride length during the approach to the board. This a result would be consistent with a relatively stereotyped run-up in subjects without peripheral vision. It suggests that long jumpers may employ peripheral vision to adjust their approach to the take-off board.

There are two broad reasons why peripheral vision may be important. Firstly information from peripheral vision gives cues about body position. Paillard & Amblard (1985) have demonstrated that peripheral vision provides information about the kinetics of limb movement, cues which can be used for the adjustment of the movement. In addition, Laurent & Thomson (1988) have shown that for accurate positioning of the foot during walking to a target, information about foot placement in the support phase is required. Removal of peripheral vision will occlude these cues about bodily movements. Secondly, Laurent, Paul & Cavallo (1988) have demonstrated that peripheral vision provides information about forward velocity during walking towards a target. When conflicting velocity cues were present in the periphery, inaccuracies in foot placement were seen. Accuracy returned to normal levels however, when peripheral vision was removed. In the study here, cues about velocity from surface texture, i.e. edge rates, would not be available when jumping with central vision alone.

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Stimulus analysis times measured from saccadic responses

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Abstract

To understand the dynamics of multiple-fixation search it is important to get insight in the underlying processes such as the analysis of the stimulus. It is difficult to estimate analysis times from a free search experiment, because in subjects, one could find different strategies. Some subjects can scan fast (short fixation durations) and make many mistakes in recognising the target, others fixate for longer and make fewer mistakes. To prevent subjects from using their individual strategies, we estimated stimulus analysis times and saccadic dead time from a controlled fixation experiment. Estimated analysis times are about 180 ms. Saccadic dead time is estimated to be about 70 ms. Our results show that a large fraction of the fixation duration is generally used for stimulus processing.

Introduction

At least three processes are active during multiple-fixation search. These processes are preparing a new eye movement, sampling of the peripheral field and analysis of the foveal target (Viviani, 1990). Recent research showed that analysis of foveal targets and preparation of saccades occur in parallel (Hooge & Erkelens, 1996). Thus, fixation duration does not necessarily reflect stimulus processing time. Still it is clear that these processes must interact at some stage, because the production of saccades has to be stopped whenever a target is found. In order to study this interaction quantitatively, we designed an experiment from which we can separately estimate foveal analysis time (FAT) and saccadic dead time (SDT). SDT is defined as the period just preceding saccades during which saccades cannot be cancelled anymore.

Method

Three subjects participated in this experiment (age 29 to 45 years). Subjects sat in front of a large screen (distance 1.50 m) in a completely darkened room. Stimuli were generated by an Apple Macintosh llci personal computer and back projected on a translucent screen (1.9 * 2.4 m) by a projection television. Eye movements of the right eye were measured with an induction coil method.

To investigate how much time subjects need to analyse the foveal part of the stimulus and subsequently to inhibit the next saccade, we engaged them in a discrimination task during rhythmic fixation. The subjects had to follow by eye a Landolt "C" (diameter: 2.1°, gap size: 0.30°) that jumped counter clockwise with a fixed frequency between the adjacent corners of a non-visible square (20° * 20°). The gap was randomly positioned in either the up, down, right or left direction. A sequence started with 6 jumps of the Landolt C during which a subject could adapt to the rhythm. Then, randomly one of the following 7 Landolt C's was replaced by a circle (diameter: 2.1°). After presentation of the circle another three Landolt "C"s followed. Subjects were asked to maintain their fixation at the position at which the circle was presented. Subjects can respond to the target in three ways. Firstly, they stop immediately on the position at which the circle appears (timely response). Secondly, they initially continue to follow the jumping stimulus but return to the position at which the circle was presented (late response). Thirdly, they do not recognise the circle at all and keep on following the jumping stimulus (false response).

We varied presentation time and counted the number of timely, late and false responses as a function of presentation time. Presentation time per stimulus ranged from 270 ms to 600 ms. For each presentation time, subjects did 100 trials.

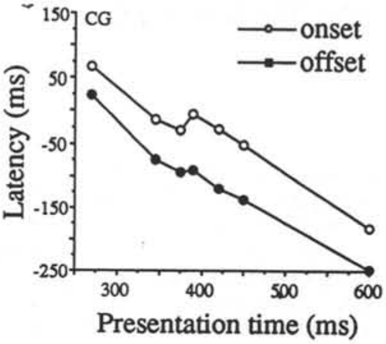

Figure 1. Onset latency and offset latency against presentation time.

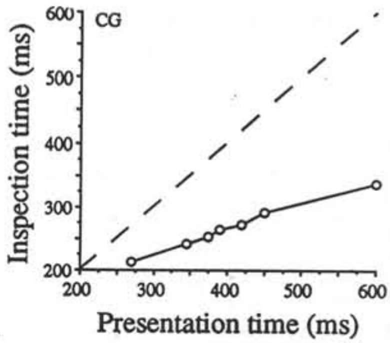

Figure 2. Inspection time against presentation time.

Results

Ideally, the presentation time of each stimulus specifies how much time is available for inspection. Figure 1 shows onset and offset latencies against presentation time. An onset latency is called negative if subjects already fixate a specific position before arrival of the stimulus. In the same sense, an offset latency is called negative if subjects already leave a specific position ahead of the stimulus. Generally, subjects were better in synchrony with the stimulus for longer presentation times. For short presentation times subjects had positive latencies. The shift of about 50 milliseconds between onset and offset latencies is due to the time that subjects need to make a saccade from one to the next position. From the onset and offset latencies and the presentation time we computed the time that was available for analysis and, if desired, inhibition of next saccades. We define this time as inspection time. The inspection time equals fixation duration minus the onset latency, if the onset latency is negative. In the case subjects show a negative onset latency they already fixate a location at which the stimulus is not yet present. Inspection occurs from the time the object appears. If fixation continues after the object has disappeared, inspection of the stimulus can still go on. Analysis only stops if a mask is presented after stimulus presentation (Eriksen & Eriksen, 1971). Inspection also stops when a saccadic eye movement is made to another target. If inspection would not stop, we would not be able to find false responses at all. Figure 2 shows the computed inspection time as a function of presentation time. Inspection time increases with presentation time with a constant of proportionality much smaller than unity.

Figure 3 shows the fractions of timely, late and false responses against inspection time. For all subjects the fraction of false responses decreases with increasing inspection time. The fraction of late responses also decreases with inspection time. The fraction of timely responses increases with inspection time.

Distribution of FAT's and values for SDT's can be estimated from these results on the basis of a simple model of the timing of visual search.

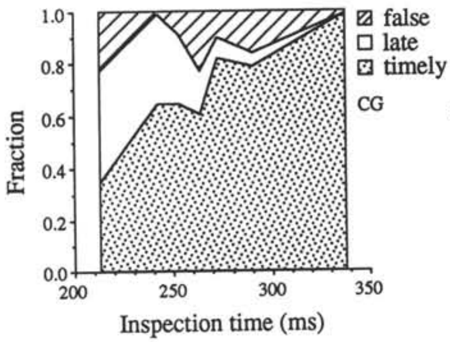

Figure 3. Fraction of false, late and timely responses against inspection time.

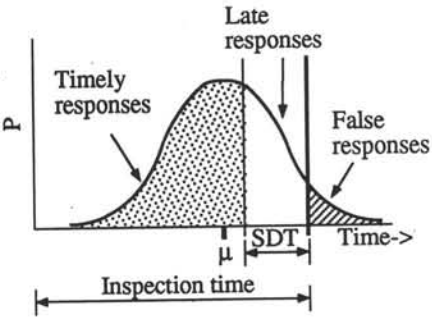

Figure 4. Determination of fraction of timely, late and false responses by the model.

Discussion and conclusion

Our model behaves like a pre-programming model (Vaughan and Graefe, 1977). In the model we implemented that the result of the analysis of the foveal target is not necessary for preparing a new saccade. The result of the analysis can only be used for cancelling a saccade. If the result of foveal analysis is available before the onset of the SDT, the model produces a timely response (figure 4). If the result of foveal analysis is available during the SDT, the model produces a late response. The response is declared false, if the result of the analysis is still not available at the onset of the saccade (the end of the inspection time). The model has three parameters. The Gaussian distribution FAT's is characterised by two parameters (μ and σ). We assume the width of the distributions of SDT's to be negligibly, so that SDT can be characterised by only one parameter. For each combination of the parameters μ, σ, and SDT, the model produces fractions of timely, late and false responses as a function of inspection time. To estimate the parameters μ, σ, and SDT for each subject, we fitted the model calculations to our experimental results. A large collection of fits was obtained by stepping through the parameter space by using steps of 1 ms for μ, σ and SDT for each measured inspection time. Minimisation of the mean square errors between the experimental results and model calculations for each measured inspection time selected the best estimations of μ, σ and SDT (Table I).

Table I. Estimations of μ, σ and SDT for three subjects.

Subject	μ (ms)	σ (ms)	SDT (ms)
CE	192	63	94
CG	175	54	55
IH	173	46	56

As far as we know, our experiment is the first attempt to measure processing times that are involved in multiple-fixation search, by using a controlled fixation paradigm. We used a controlled fixation paradigm because in a free search experiment it is difficult to manage that subjects scan at prescribed fixation rates. The different types of saccadic responses reveal the progress of the stimulus processing as a function of time. Estimations of FAT's show that a large fraction of the fixation durations, that last about 200 ms to 300 ms during multiple-fixation search, is used for stimulus processing.

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Smart Mechanism for Time To Contact Detection

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Abstract

It has been shown that the optical variable *tau* specifies the time to contact (TTC) of an object approaching an observer (Lee, 1976), i.e. for expanding flow patterns. The definition of tau may be extended to specify TTC of non-approaching objects, i.e., for flow patterns that show motion parallax. However, the way tau is registered by the visual system has been rather neglected in the literature. In this connection, an elegant visual mechanism for tau detection is presented, based upon elementary motion detectors only.

Introduction

In interaction with the environment, timing of actions is of vital importance (see Tresilian, 1995, for a review). In this respect, Purdy (cited in Schiff, 1965) introduced the concept of time-to-contact (TTC). TTC can be defined as the momentary distance between two objects divided by their (assumed constant) relative speed. However, even when TTC is an important variable, the way TTC is registered by the visual system has received little attention. Before we show that TTC can be perceived by a smart mechanism based upon elementary motion detectors only, we will first consider the visual information on TTC.

The *optic array*, observed at a *point of observation* (Gibson, 1950), comprises light patterns depicted by the projection of objects in the environment. When the point of observation is translated relative to the environment (or vice versa), two basic types of *optic flow* can be observed, depending on the direction of translation with respect to the viewing direction (Koenderink, 1986). First, when translating along the viewing direction, optical patterns show expansion. For such expanding patterns, Lee (1976) has shown that an optical variable named tau, the ratio of the angular size and rate of expansion of a pattern, is equal to the TTC of the object depicting the pattern (for small visual angles). Second, when translating perpendicular to the viewing direction, optical patterns show motion parallax. Analogous to expanding patterns, a similar tau measure exists for parallax flow patterns, which specifies TTC of objects with the line or 'plane' (Cutting, 1986) of sight, i.e., the visual angle between the object and the line or plane of sight, divided by the rate of contraction of that angle. At intermediate viewing directions combinations of expansion and motion parallax patterns are observed, which require combination of the two tau measures (see Bootsma and Oudejans, 1988)

Smart mechanism for tau detection

Even when visual angle and angular speed are 'optically given', how does the visual system compute tau? Are we to assume that the nervous system computes tau by dividing visual angle and rate of expansion? (van de Grind, 1990). Basically, there is no reason to assume that the nervous system performs this kind of computations (van de Grind, 1988; Barlow, 1986). More likely, the brain comprises so called *smart mechanisms* (Runeson, 1977), which allow direct registration of high-order variables, without necessarily starting with the constructs that are basic to physics (van de Grind, 1988). We will illustrate the concept of smart mechanisms with an elementary motion detector, which, as we will show, may be regarded as a tau detector as well.

It is generally accepted that angular motion is registered by a neuronal mechanism that correlates the output of two nearby receptive fields (a *bilocal correlator).* Bilocal correlators respond optimally to stimuli that show motion with a specific motion vector (speed and direction). Bilocal correlators are smart mechanisms for motion detection, since they allow direct perception of motion without doing any 'computations'. Their smartness is not an 'algorithm' that 'computes' motion information in stimuli, but is a product of the connection of two receptive fields. The output of a bilocal correlator is a *labelled line*, i.e., when active, a stimulus is moving with a specific motion vector over its receptive fields. Since they are only sensitive to one motion vector, at a specific position on the retina, large numbers of bilocal correlators analyse the visual information in parallel (van Doorn & Koenderink, 1983).

The 'smartness' of the bilocal correlator in the detection of tau is that it combines angular motion and visual angle. At a specific retinal position, i.e., at a specific visual angle with respect to the fovea, bilocal correlators respond to a specific motion vector. Thus, *a bilocal correlator will respond to stimuli with a specific tau value.* As such, tau is registered without doing any 'computations': it follows from the combination of the motion sensitivity of bilocal correlators and their location on the retina.

Since large numbers of bilocal correlators exist throughout the visual field, a flow pattern (expansion, parallax or a combination) with a certain tau value will always activate (a subset of) a specific array of bilocal correlators. Figure 1 (left panel) shows an example of an array of bilocal correlators tuned to a parallax flow pattern with tau = 4 s. Obviously, there are many different bilocal correlator arrays, tuned to different tau values for different types of optic flow: Figure 1 could also have depicted an array of bilocal correlators tuned to an expanding pattern with tau = 1.3 or 5.0 s. The current smart mechanism allows tau detection that does not depend on pattern content: any expanding pattern (or parallax pattern etc.) with a certain tau value will activate a (subset of) the same array of bilocal correlators. Thus, the current smart mechanism allows object invariant TTC perception.

The use of bilocal correlators as tau detectors has one binding condition: the fovea has to fixate a point in the flow pattern. However, when not making saccades, the fovea *is* always fixating a point of interest. When the point of interest moves, smooth pursuit eye movements are made to keep track of it (Young, 1971). Such pursuit eye movements will generate additional 'optic flow', i.e., a rigid translation of the information in the optic array (Koenderink, 1986). Such a rigid translation does not alter the relative flow in patterns due to translation. Figure 1 shows examples of a motion parallax pattern with and without eye pursuit. Note that the flow pattern is identical, irrespective of additional translational flow due to pursuit eye movement.

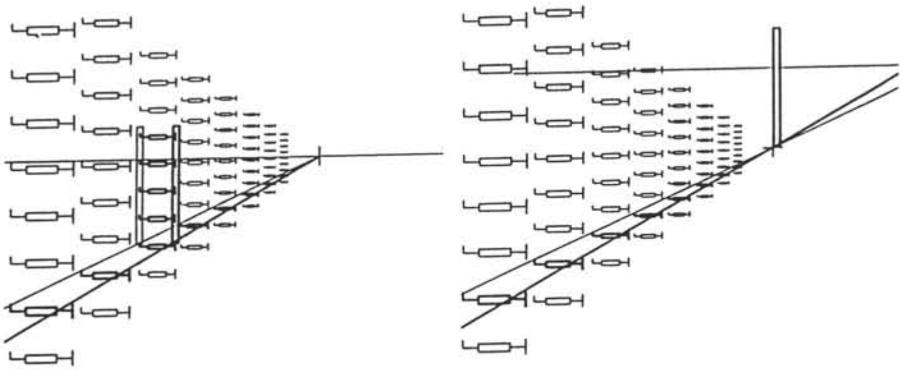

Figure 1 depicts an array of bilocal correlators, all tuned to a motion parallax pattern with tau = 4 s. Large detectors are tuned to high angular speeds, small detectors, near the fixation point (the cross) are tuned to low angular speeds. The stimulus pattern, depicting a line and a pole on a horizontal plane, is drawn in thick lines (current status) and thin lines (status 1 s earlier). Bilocal correlators responding to the stimulus pattern are drawn in thick lines. The left Figure shows the stimulus pattern while fixating the vanishing point of the line. The right Figure depicts the same pattern while fixating the bottom-left corner of the pole. *Whether or not eye pursuit movements are made, a subset of the same array of bilocal correlators is activated*. Other flowtypes, e.g. expanding patterns or combinations of expansion and parallax, would require a different array of bilocal correlators to be registered.

But, even when the smart mechanism suggested here is elegant and parsimonious, aren't there any disadvantages of such a mechanism? Well, there are. First, it does not handle approaching objects that rotate, since they depict flow patterns that are more complex than the expanding and parallax patterns generated by translation. However, objects moving in such a way are rare, and Simpson (1988) has found that their TTC discrimination thresholds are elevated when compared with normal approaching objects, which indicates that rotating approaching objects are perceived less accurately than normal approaching objects. Second, implementing such a smart mechanism would require that for each tau value of each flow pattern (expansion, parallax or their combination) a separate array would have to be sampled.

Conclusions

The smart mechanism for TTC detection proposed here has a number of interesting features. First, it is able to register tau in expanding patterns as well as in patterns that show motion parallax. Thus, it is able to explain TTC perception of objects and observers translating in any direction. Second, it allows object invariant TTC detection: any pattern with a certain tau value will be registered by (a subset of) the same array of bilocal correlators, regardless the size, shape or approach speed of the translation that depicted the flow pattern (provided that the angular size and rate of expansion of the pattern are within detection limits). Third, the idea is compatible with Gibson's notion of 'direct' perception: the mechanism is able to directly register the tau information contained in a flow pattern. Finally, it is a parsimonious mechanism, which is based on mere low-level, biologically plausible, neuronal circuitry. Disadvantages are that it would require sampling a large number of different bilocal correlator arrays, and that it cannot handle rotating approaching objects.

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Differences between Haptic and Visual Judgements of Curvature

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Abstract

Large systematic scale differences show up when subjects are asked to match the curvature of a haptically presented surface with a visually presented cross-section. Scaling factors ranging from 0.3 to 3.0 are found. Most often haptically estimated curvature is overestimated relative to visual curvature. Therefore, we conclude that is it highly unlikely that one modality calibrates the other. The results for left and right hand are not significantly different.

Introduction

It has long been thought that haptic experience is necessary for the calibration of the visual system (e.g., Locke, 1689; Berkeley, 1709). The prevailing idea was that the sense of touch provided the observer with veridical information about the shape of things in the environment. However, the experiments of, among others, Gibson (1933), Rock and Harris (1967) and Power (1980) have shown convincingly that vision dominates in situations where vision and touch provide conflicting information. Moreover, even in the absence of visual information haptic judgements are seldom veridical (e.g., Vogels, Kappers & Koenderink, 1996).

Here we are interested in the question how well observers can match visual and haptic curvature in a situation without any conflicting information. If the visual system is calibrated by input from the haptic system (or vice versa) we do not expect to find any systematic differences. If, on the other hand, the calibration processes of the two senses are more or less independent, the relationship between haptic and visual judgements of curvature cannot be predicted. Deviations from a one-to-one relationship between haptically and visually judged curvature are possible and expected in such a case.

Another motivation for this study is that in previous research we repeatedly found that performance in bimanual discrimination tasks is worse than performance of both hands separately (e.g., Kappers, Koenderink, Te Pas, 1994). Such results might possibly be explained if the hands are calibrated independent of one another. The matching task we use here, provides us with a tool to gain insight into the relative calibration of the two hands.

Methods

Subjects were asked to haptically explore a cylindrical surface which was presented to them behind a curtain so that they could not see it. Visual stimuli were presented in a folder in front of the curtain. Each page of this folder contained a possible cross-section of a cylindrical surface. Task of the subjects was to indicate which of the visually presented cross-sections corresponded best to their estimation of the curvature of the haptically presented surface. Visual and haptic stimuli were presented at about the same distance from the subject.

The haptic stimuli were 20 cm in diameter and made out of polyurethane foam impregnated with synthetic resin. The bottom of the stimuli was flat and always rested on the table; the upper surface was cylindrically curved. The base height of the stimuli was different for each stimulus so that the total height was not a cue for curvature. The following curvatures (reciprocal radius) were used: -5.7, -4, -2.8, -2, -1.4, -1, -0.7, -0.5, -0.35, 0, 0.35, 0.5, 0.7, 1, 1.4, 2, 2.8, 4, 5.7 (1/m). The set of cross-sections contained the same curvatures but in addition also -22.6, -16, -11.3, -8, 8, 11.3, 16, 22.6 (1/m) were available. Since a cross-section of a curvature of 0.35/m is almost indistinguishable from a straight line, it was not necessary to add curvatures in the lower range. Subjects were explicitly told that the curvature ranges of the haptic and visual stimuli were not necessarily identical.

Each cylindrical surface was presented 10 times to the subject in random order. Exploration time was unlimited. On average, a complete session took about 2.5 hours. Right and left hand were tested in different sessions on different days.

Three naïve subjects participated in this experiment. IV and KK were dominantly right-handed, whereas WH was dominantly left-handed according to the definitions of Coren (1993).

Results

The results for all three subjects are shown in Figure 1; the visually matched curvature is given as a function of the haptically presented curvature. The error bars show the standard deviations in the 10 repeated trials of a data point. The straight line in each of the graphs shows where measurements should lie if haptically and visually presented curvature match exactly. Clearly, for none of the subjects this is the case, although the results of subject WH come close.

We fitted straight lines through the data points, which in all cases yielded correlation coefficients above 0.9. The ratio of the slopes of these lines with the drawn line (slope of 1) gives an indication of the relative under- or overestimation of haptic curvature with respect to visual curvature. Subject IV relatively overestimates haptic curvature with a scaling factor of 2.2 for the left hand and a scaling factor as large as 3.0 for the right hand. Also subject WH shows a small overestimation of haptic curvature: 1.4 for both the right and the left hand. In her case, deviations mainly occur for the higher curvatures. Subject KK, on the other hand, underestimates haptic curvature relative to visual curvature (0.3 for the left hand, 0.6 for the right hand). Pilot studies with three more experienced subjects showed behaviour similar to that of subjects IV and WH. Their scaling factors lie between 1.4 and 2.5.

Results for the left and the right hand were always very similar. None of the subjects showed an overestimation for one hand and an underestimation for the other. The differences between the scaling factors of the right and the left hand were only small and they were largest for subject IV.

Discussion

These matching experiments reveal large differences between haptically and visually judged curvature. Most subjects overestimate the curvature of the haptically presented surface with respect to the visual cross-sections. This finding agrees with our own introspective experiences that surfaces which are first touched and then seen look much more flat than expected. For this reason it is tempting to locate the source of this mismatch somewhere in the haptic system, but there is a snag in it: if the visually presented cross-sections could have been touched they probably would appear much more curved than expected. One conclusion can be drawn with certainty, namely that at least one of the two modalities does not provide the observer with veridical information.

Our results make it highly unlikely that one of the modalities calibrates the other because in that case one would not expect the large systematic differences we find.

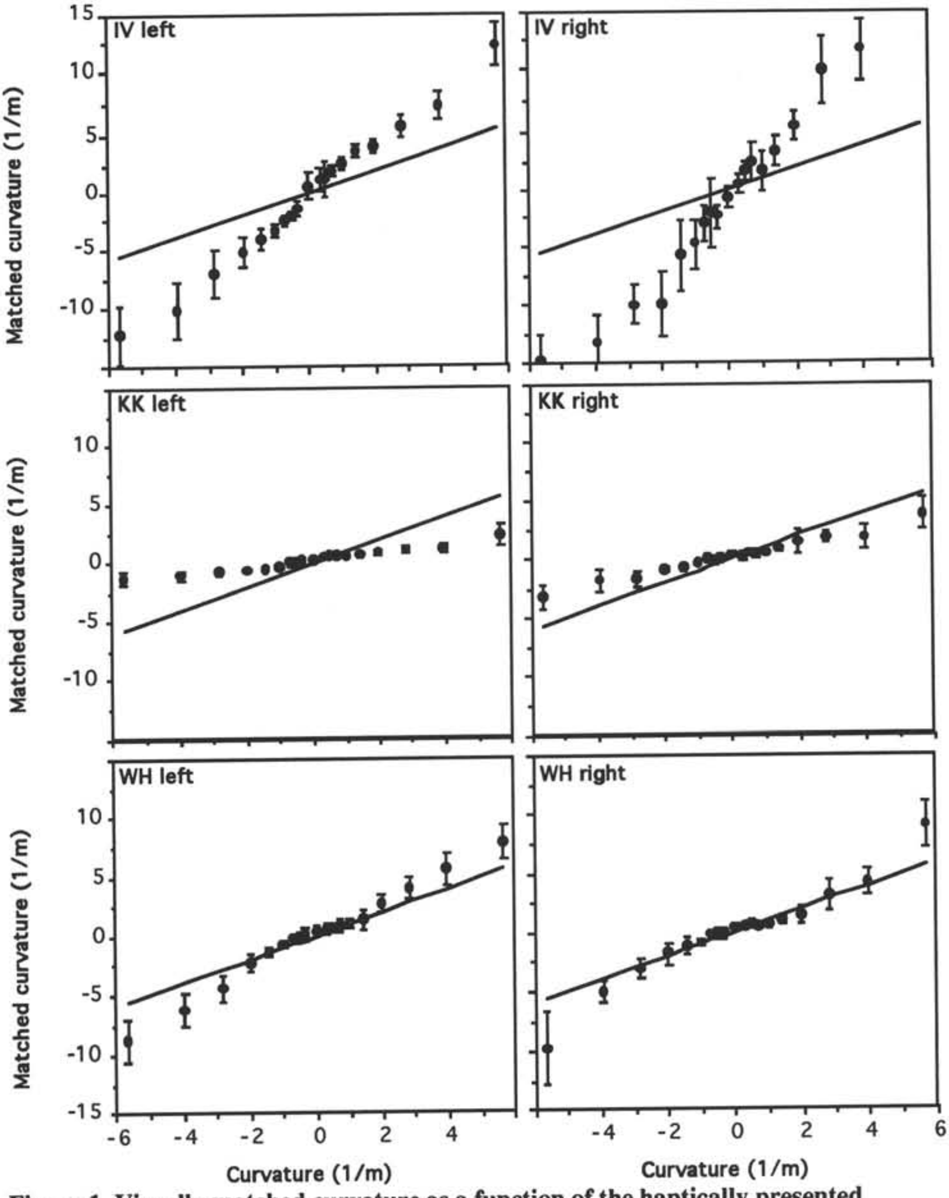

Figure 1 Visually matched curvature as a function of the haptically presented curvature. Perfect correspondences would lie on the straight lines. Error bars indicate standard deviations from the 10 trials. Left and right refer to the hand used to touch the surfaces.

However, we can neither conclude that the two modalities are completely independent, since in conflicting situations vision certainly influences haptic perception (Gibson, 1933; Rock & Harris, 1967; Power, 1980). Clearly, more research is needed to shed light on this issue.

Since for all subjects the results for the left and the right hand are very similar, we do not think that the calibration processes of the two hands can be totally independent. If that would be the case, much larger differences are to be expected. As a consequence, independent calibration processes of the two hands can be ruled out as an explanation of the relatively poor performance we found in bimanual discrimination tasks. Part of our future research will be focussed on investigating alternative explanations.

Acknowledgement

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Postural Control of Equilibrium in the First Year of Learning to Walk

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Abstract

The development of independent walking is considered here as the process of learning dynamic equilibrium. 7 children have been observed from onset of walking up to 2 years later. Locomotor parameters were recorded by a large force–plate synchronised with four video cameras. The developmental trend observed in limb kinematics is analysed within the system/task model (Newell, 1986). The child strategy at various periods of learning to walk is interpreted as a motor solution to a motor problem : the mastering of disequilibrium during the single–support phase of the step cycle.

Introduction

While almost all children are biologically prepared for bipedal locomotion – biomechanical and neural development are in place at 12 months or so – we argue here that walking itself is learned. That is, biological preparation allows the child to begin to experience the unique patterns of destabilizing forces associated with the body in such a task.

One of the main problems encountered by the young toddler at onset of walking is the control of equilibrium. To control equilibrium is to control the relative position of the centre of mass (CM) and of the centre of pressure (CP) in relation with the base of support (Winter, 1992; Bril & Brenière, 1992). During the step cycle the unipodal stance is the period of greater disequilibrium (Yang, Winter & Wells, 1990) as the projection of the centre of mass onto the ground falls outside of the base of support.

Model

Two conditions are required to insure the equilibrium of an object :

1 – The resultant of the external forces – gravitational forces and ground reaction forces – must be equal to zero.

2 – The sum of the moments of the forces with respect to the centre of mass must be equal to zero.

A corollary of these conditions is a null distance between the centre of foot pressure (CP) (that is the barycentre of the reactive forces) and the projection onto the ground of the centre of mass (CM).

In walking, during the single support phase the projection of the centre of mass falls outside the surface of support. However the walker will not loose balance owing to constant postural adjustments which stabilise the body in an upright position.

Purpose of this study

Before his/her first attempt to walk without support, the young child has never experienced a unipodal stance situation, that is a situation of disequilibrium. How, in the early months of walking, does the toddler succeed to overcome such a situation. That is, how does he/she learn to master gravitational forces so as to avoid falling and to propel herself forward? The aim of this study is to analyse the strategy used by the child to overcome disequilibrium and its developmental trend, during the first year after onset of independent walking.

Hypothesis

To overcome disequilibrium, the child tends to reduce 1/ the duration of the disequilibrium phase of the step cycle, that is the single support phase, and 2/ the distance between the centre of mass and the centre of foot pressure. An increase in postural control will allow for a greater distance between the centre of mass and the centre of foot pressure and will then permit an increase in step length and consequently in speed of walking.

Methods

Subjects

– 6 children observed once a month for one year after onset of independent walking, and once every three months during the following year. In each session of observation the child performed 20 to 30 sequences of steps on the force–plate; each of these contained 5–8 steps.

Experimental devices

Locomotor parameters were recorded by means of a large force–plate (1 by 2 m) synchronised with four video cameras.

Parameters under study

– Kinematics of the leg segments of both legs during the whole step cycle, and angular values of shank and thigh of both legs at the very end of the single stance (period of maximal disequilibrium) relative to the vertical, along the antero–posterior axis.

– Values of the centre of foot pressure during the step cycle.

– Duration of swing and double–support.

Results

During the first months of learning to walk, the typical developmental trend observed in previous studies (small length of step, wide steps, increase followed by a decrease of frequency of steps, etc.) go with important variations of the kinematics of the leg segments. Data show that :

– At onset of independent walking the thigh segment of the stance leg rarely overpasses the vertical so as to avoid a situation of disequilibrium. This strategy goes with short step length (step length doubles within the first months after onset of walking).

– During the first weeks after onset of independent walking the displacement of the centre of foot pressure (CP) shows very different features from what can be observed a few months later. Instead of shifting smoothly from one foot to the other during the double–support phase, the displacement of the CP corresponds to a two phases displacement, with a stop in between. Concurrently, the relative values of the double–support phase are very high (50 to 70 % of the cycle).

Discussion

The developmental trend observed in limb kinematics is analysed within the system/task model (Newell, 1986). The child strategy at various periods of learning to walk is interpreted as a motor solution to a motor problem : the mastering of disequilibrium during the single–support phase of the step cycle.

While the child has never experienced such a situation of disequilibrium, he/she has to *learn* how to produce sufficient forces at the leg joints (hip, knee, ankle) to overcome disequilibrium and to be able to move his/her body forward during the single–stance phase as it is the case in adults. During a first phase the child goes through the "discovery", through practice, of the invariant organisational properties of the movement, that is the dynamics of the body while solving the motor problems involved in walking. A consequence of which is a possible increase of the distance between the centre of foot pressure and the projection onto the ground of the centre of mass along the antero–posterior axis, allowing for a more efficient step.

The approach developed here suggests that there is no need to refer directly to the neurological maturation of the central nervous system to explain some of the important changes observed in early gait. An action system approach could help to propose a new way to examine the acquisition process, emphasising the relationship between the capabilities of the child and the properties of the task, in the motor solution adopted.

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Effect of Ball Mass and Ball Momentum in Interceptive Task

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Abstract

The effect of mechanical constraints, such as mass and momentum, of an approaching object on an interceptive behaviour are studied. Subjects had to hit with a backward-forward movement a ball traveling at constant velocity. The perception of the mass of the three different balls used in this study was achieved by the subject manipulating them before performing the task. Results showed an effect of mass on maximal movement velocity but no effect on time-to-contact at movement initiation. This suggests that object mass and momentum are taken into account in the control of the movement but not in its timing.

Introduction

In order to intercept successfully an oncoming object, the actors action needs to match the constraints of the task (Newell, 1986). Amongst these constraints, the importance of timing has been frequently emphasized (e.g., Bootsma & Van Wieringen, 1990). However, other constraints, such as mechanical constraints, also have to be matched (Li & Laurent,1995). It has been proposed (Stoffregen, Henderson & Sasaki, 1995) that the momentum of an object to intercept should be taken into account in movement control. Although the effects of approaching velocity on the characteristics of the actor's movement have been investigated (e.g., Li & Laurent,1995), little evidence has been given so far on the role of object's mass and object's momentum per se. Therefore, the aim of this study was to investigate to what extent the anticipated mass of an approaching object affects the characteristics of an interceptive action. What kind of effect an increase of the mass of an object to intercept could have on the actor's action? For the same velocity, increasing the mass of an object increases its momentum. To perform an action which would have the same effect on the object to hit, e.g. knocking it out of the trajectory, one's has to match the increase of its momentum. Increasing movement velocity would produce the desired effect. It is hypothesized that increasing the mass of the object to hit would lead to an increase in the maximum velocity of the actor's movement.

Method

Thirteen right handed male subjects volunteered to take part in the experiment. They were required to hit an approaching ball with a backward-forward movement. To strike the ball subjects manipulated a bat (17.5 cm high by 3 cm wide). Three balls of the same diameter (6.5 cm) but with different weight (B1: 10 gr.; B2: 20 gr.; B3: 200 gr.) and slightly different colors (B1: pink; B2: yellow; B3: orange) were attached on a trolley. An electrical motor (Hitachi DV10DA) pulled this trolley along a linear track (6 m long) at three different velocities (1.5, 2.0 or 3.0 m/s). After the initial acceleration on 1 metre, the velocity of the trolley remained constant. Ball and bat movements were recorded using the movement analysis system Elite at 100 Hz with two markers located on the ball and on the bat.

Subjects were asked to hit the ball with the bat. Starting position at the future interception point was standardized. No constraint was imposed on when to initiate the movement nor on how hard to hit the ball. Before the experiment the three balls were presented to the subjects who were invited to manipulate them. Before each trial, the ball used was presented again and manipulated by the subjects to ensure that they were well informed on the type of ball they had to hit. It has been shown that some object's physical characteristics could be perceived through interaction phenomena (e.g., Runeson & Frykholm, 1983; Flynn, 1994). As such interactions were not present in the setup used in the present experiment, it seems that the visual perception of ball mass during the approach can be ruled out. However, through the manipulation of each ball before performing the task, it is argued that ball mass could be perceived using haptic information before the action.

Three dependent variables were analyzed: time-to-contact (Tc) when movement was initiated, maximum linear velocity of the bat and amplitude of the bat's displacement. A two-ways ANOVA with repeated measure on ball mass and ball velocity were performed separately for each dependent variable.

Results

The analysis of variance on maximum movement velocity showed a significant main effect of both factors ball mass and ball velocity (mass: $F(2,24)=9.25$; $p<.001$; velocity: $F(2,24)=13.76$; $p<.001$). The maximum movement velocity increased with the increase of ball mass (Figure 1) and ball velocity. The interaction between mass and velocity was found significant ($F(4,48)=4.02$; $p<.01$), with movement velocity increasing with both ball mass and ball velocity.

The analysis of variance on movement amplitude showed that the main effects of mass and velocity were significant as well as their interaction (mass: $F(2,24)=11.29$; $p<.0001$; velocity: $F(2,24)=4.68$; $p<.05$; mass x velocity: $F(4,48)=2.96$; $p<.05$). Amplitude increased with the increase of mass and velocity.

Tc at initiation time showed different effects. Ball velocity had a significant main effect ($F(2,24)=8.18$; $p<.01$): Tc decreased with the increase of ball velocity. However, ball mass and the interaction mass x velocity were not found to have a significant effect on Tc (mass: $F(2,24)=0.65$; ns; mass x velocity: $F(4,48)=1.05$; ns).

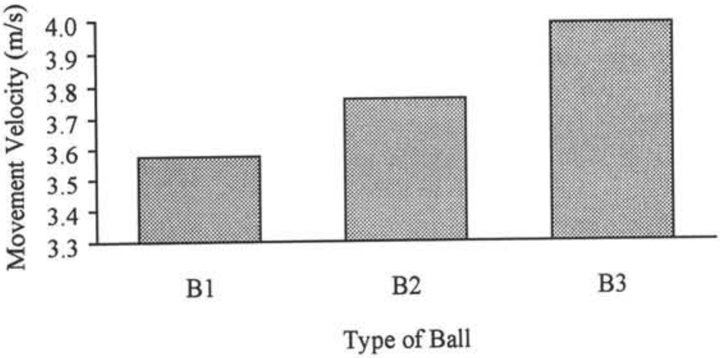

Figure 1: Effect of ball mass on movement velocity.

Discussion

The results of movement velocity and movement amplitude showed that the mass of the oncoming object and its momentum are taken into account in the control of the interceptive action. However, the absence of effect of ball mass on Tc at initiation time suggests that the timing of the movement is not linked with this property of the object to intercept. The effect of ball velocity on Tc at initiation time reproduces the results already reported elsewhere (e.g., Li & Laurent, 1995). The perception of ball's mass before performing the action and the various effects of ball's mass on action parameters will be discussed successively.

With the setup used in the experiment reported here, the mass and the momentum of the approaching object could not be directly perceived by the subjects through an interaction phenomena such as a collision (Runeson & Frykholm, 1983). The present study didn't address the perception of such mass and momentum, but merely the effect of an anticipated mass on an interceptive behavior. However, the mass of the object could be perceived through (i) the manipulation of the ball before each trial, (ii) through a code of color and (iii) through the instruction given to the subject. The data showed that the different balls have elicited different behaviors. This suggests that each ball have afforded a different type of action, i.e. an increase of movement velocity with balls' mass. Further work, addressing in particular the use of haptic information to perceive the characteristics of an object before performing a task, is necessary.

It can be argued that movement amplitude and movement velocity should be logically linked with the mechanical properties of the object to intercept, e.g. its momentum, when movement timing should be linked only with the object properties which affect the approaching timing, e.g. velocity. Following this line of thoughts, it is not surprising that ball mass, which has no link with the timing of the object approach in the setup used, has no effect on Tc at initiation time. However, this rational doesn't stand when a more global view of the movement is considered. Timing depends on movement amplitude and movement velocity. These three parameters of the movements are linked, and only an adequate coordination of them in view of the characteristics of the approaching object can lead to a successful behavior. In the present study, it seems that by increasing movement amplitude and movement velocity, Tc has been kept independent from the momentum of the object to intercept. The challenge is now to understand how subjects are using these three degrees of freedom, i.e. amplitude, velocity and timing, to perform a successful interceptive action when the properties of the approaching object are modified.

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This study was conducted while the author was at the Manchester Metropolitan University, UK.

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Direct Perceptual Bases for Intuitive Estimates of Correlations

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Abstract

A series of experiments is reviewed that assess the perceptual bases of correlation estimates from scatterplots. Results show that a simple psychophysical function, based on the geometric dispersion of the points, accounts for most phenomena that were reported in the literature on correlation estimates from scatterplots. The search for perceptual variables that provide the information for intuitive judgments may constitute an additional important contribution of ecological psychology.

Introduction

Ecological psychology has devoted only limited attention to subjective judgments that are based on static displays. This issue may seem at first remote from the ecological paradigm. However, intuitive judgments do form a central part of many decision making processes and their understanding may be of both theoretical and practical importance. Currently only very little is known about the ways by which intuitive judgments are formed (Mahan, 1994). I would like to argue that the ecological approach to perception and action can provide important new insights to this issue by determining the possible perceptual bases of these decisions.

The claim can be demonstrated through one particular type of intuitive judgment - the estimation of correlations from scatterplots. A number of studies have attempted to assess the mechanisms by which people estimate correlations. These studies revealed various variables that affect estimates while leaving the statistical correlation coefficient unaltered: Correlation estimates depend on the slope of the point cloud (i.e., the aspect ratio of the axes), with increasing the length of the Y - axis leading to an decrease of the estimates (Meyer & Shinar, 1992). Also, simply reducing the overall size of the point cloud leads to an increase in estimates (Cleveland, Diaconis & McGill, 1982). The perceptual properties of the displays have similar effects on correlation estimates of people with different levels of statistical training, ranging from university lecturers in statistics to undergraduate students without statistical training (Meyer & Shinar, 1992). These phenomena indicate that estimates are based on visual properties of the displays, rather than on statistical knowledge. Hence the search for the perceptual basis of these estimates seems justified.

The experiments

A number of experiments were conducted to test this hypothesis (Meyer, Taieb and Flascher, 1995). All experiments used the same technique: Participants received booklets that held scatterplots, and their task was to assess the degree of correlation between the two variables in the scatterplot on a scale from 0 to 100.

In the first experiment participants evaluated scatterplots with correlations ranging from $r^2=.04$ to $r^2=.99$. An attempt was made to determine which geometric property of the point cloud best allows to predict estimates. Various perceptual variables that could account for estimates were inspected. Eventually it was possible to predict estimates through the function

$$r_{est} = 100 - a * M|d|^b$$

where M|d| is the mean of the absolute perpendicular distances of the points from the regression line, and *a* and *b* are coefficients. The value of *b* was determined to be .648.

Two additional experiments were conducted in which the slope of the point cloud, the number of points that were displayed and the presence of outlying data points were manipulated. Participants in the experiments varied in their statistical training, with some groups having extensive experience in statistics and others having no experience at all. Figure 1 shows the mean estimates for the various conditions in the two experiments as a function of the presented correlation. The figure shows that for the same level of correlation a wide range of estimates was obtained, depending on the experimental conditions.

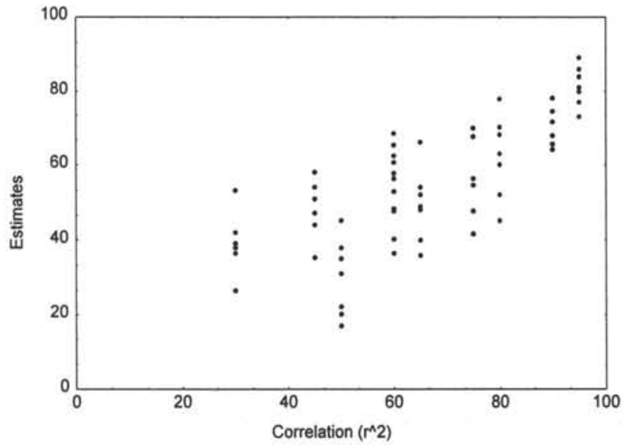

Figure 1: Correlation estimates for various conditions in two experiments, as a function of the displayed correlations.

An attempt was made to fit the function that was found in Experiment 1 to the data of Experiments 2 and 3, using the same exponent *b* as in Experiment 1. The coefficient *a* determines the scaling of the numeric values and may depend on the range of stimuli that are used in a study. It is likely to differ between experiments, and therefore for each experiment a different value of *a* was computed. Figure 2 presents the intuitive estimates in Experiments 2 and 3 as a function of the predictions from the perceptual function. This function explains 92% of the variance of estimates, compared to 57% that are explained by the statistical correlation.

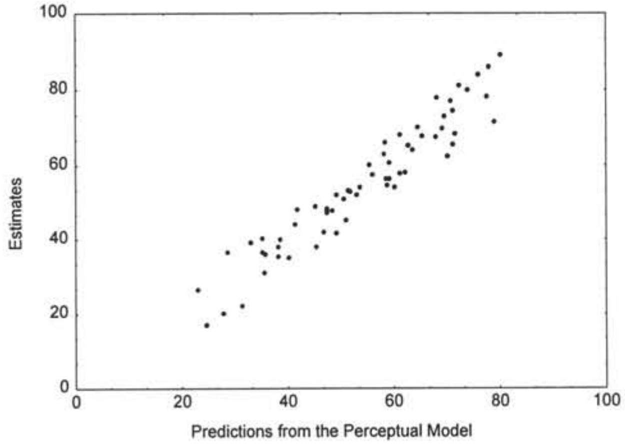

Figure 2: Correlation estimates as a function of the predictions from the perceptual model.

Conclusions

This study shows that intuitive estimates of correlations from scatterplots can be predicted from the mean dispersion of the points from the regression line. It seems that correlation estimates are essentially judgments of "badness of fit", based on the dispersion of points. The model accounts for a variety of effects that are known from research on correlation estimates.

Obviously people do not measure the distances of the points and compute the mean of the absolute distances but rather are able to build some assessment of the degree of dispersion in the cloud by a rapid inspection of the point cloud. The process indicates that certain properties of the point cloud are directly perceived.

This analysis of an intuitive judgment demonstrates the viability of the search for the perceptual basis of intuitive estimates. A similar approach can probably be applied to other types of judgments. The attempt to account for the perceptual information that forms the basis of intuitive judgments in various domains may be a new challenge to psychologists from an ecological background.

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Toward a Dynamical Account of Trajectory Formation: Emergent 1D and 2D Trajectories

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Abstract

Following Schöner (1990, 1994), the conditions for a minimal dynamical model capable of qualitatively reproducing the main kinematic features of human trajectory formation as emergent properties of the dynamics of the model are examined. A cubic stiffness function and a Rayleigh damping function were identified as the minimal components of a model which can reproduce the kinematics observed in 1D and 2D speed-accuracy trade-off tasks. Different implications of such a model are discussed.

Introduction

Trajectory formation is an important issue in motor control research, traditionally addressed from the point of view of movement planning. This classical view of motor control emphasises optimisation principles responsible for the reduction of degrees of freedom (e.g., the minimal jerk-model: Viviani & Flash, 1995). Recently, it has been shown that the principles of dynamic pattern theory that explain interlimb coordination can successfully be reinvested to account for different aspects of trajectory formation (Schöner, 1994). This alternative approach emphasises the self-organisational capabilities of the motor system and tries to explain the kinematic properties of human upper limb movements using dynamical models and task-related spaces and/or variables.

The dynamic approach makes a difference between a macro-scaled autonomous emergent organisation (the observed movement), and micro-scaled fluctuations around the dynamic pattern (random noise). The observed movement in the task space is considered an autonomous (i.e., not time dependant) dynamic pattern, hence better represented in a time independent manner using phase portraits (position vs. velocity) or, as suggested by Guiard (1993), using Hooke's portraits (position vs. acceleration). The typical equation of such an autonomous dynamic system is (Beek and Beek, 1988):

$$\ddot{x} + \mathrm{f}(x,\dot{x})\dot{x} + \mathrm{g}(x) = 0 \qquad (1)$$

The function $\mathrm{f}(x,\dot{x})\dot{x}$ represents the *damping* (velocity related dissipative terms) which is mainly related to the stability of the motion pattern. This damping function defines the shape and attractiveness of the limit path towards which the behaviour converges in the phase portrait (e.g., a point attractor in the case of postural behaviour or a limit cycle for a self sustained rhythmic movement). The function $\mathrm{g}(x)$ represents the *stiffness* (position related conservative terms) which is primary related to the frequency of the movement. This stiffness function defines the shape of the path towards which the behaviour converges in the Hooke's portrait.

Schöner (1990, 1994) demonstrated that it is possible to capture the major features of human movement (i.e., cyclical self-sustained oscillations, point-to-point discrete movement and postural behaviour) using a relatively simple dynamical model similar to equation (1). With respect to trajectory formation, several well-known aspects of one-dimensional and two-dimensional movements emerge from the intrinsic dynamics of this model. For example, the 2/3 power law linking curvature and angular velocity in handwriting and drawing is an intrinsic feature of the emergent trajectory.

However, the most important point in this work might be that insistence on the fact that the behavioural capabilities of the model are rooted in the bifurcation properties of the dynamics. Thus, to reproduce human basic behaviours, a (comprehensive) dynamical model must combine two different kinds of bifurcation within equation (1). First, a pitchfork bifurcation must be present in the stiffness function (a single stable point giving way to two stable points) to account for the postural and point to point movement behaviours. Second, a Hopf bifurcation in the damping function (a point attractor giving way to a limit cycle attractor) allows to account for self sustained oscillations (and for the kinematics of the motion between two points in the discrete case).

In the present contribution, the pioneering work by Beek and Beek (1988) and Schöner (1990) serves as a departure point for moving toward the establishment of a minimal dynamical model capable of qualitatively reproducing the main features of human trajectory formation as emergent properties of the dynamics of the model.

Experimental data

Method

In the first experiment, the subjects were asked to perform a sustained back and forth, drawing a continuous line intersecting two targets of variable sizes and distances (ID ranging from 3 to 5). This continuous Fitts' task can be described as an oscillation in a one-dimensional task space (i.e., the main axis linking the centres of the targets). Orthogonally combining two such Fitts' tasks defines a two-dimensional task space where the motion can be described as two coupled oscillations (i.e., one for each couple of opposite targets) giving way to elliptical motion of the end-effector (Mottet et al., 1994). In the second experiment, the task was to draw a continuous line while sequentially passing through each of four targets (i.e., one target at the top, bottom, left and right extrema of the required ellipse).

Experimental data was recorded using a graphic tablet (A3, 163 Hz, ±0.25 mm) equipped with a non marking stylus. For a each 15 seconds recording trial, the subjects were instructed to go as fast as possible with less than 5% spatial errors. Before analysis, the many cycles recorded during a trial were normalised and averaged: This normalised average cycle is supposed to reflect the autonomous dynamic organisation which emerges to respond to the task demand.

Results

In both the one-dimensional and two-dimensional experiments, the non-linear contribution to the motion tended to increase with the relative spatial precision requirements: For the lowest requirements, the motion was harmonic. When non-harmonic, the one-dimensional and two-dimensional Fitts' tasks led to different dynamical behaviours:

— The stiffness function, which can easily be assessed via Hooke's portraits (position vs. acceleration, figure 1: bottom), exhibited either a softening spring (one dimension) or a hardening spring (two dimensions) behaviour.

— The damping function was more difficult to qualitatively assess through graphical representation. However, in all our experimental data, the speed profile asymmetry always showed a longer deceleration phase (figure 1: top), leading to a phase portrait skewed to the right (figure 1: middle).

Discussion

These results can only partly be accounted for using Schöner's (1990) model in which the stiffness is a Duffing function (up to the 5th power of position) and the damping a Van der Pol function (i.e., dissipative constraints creating a limit cycle related to an amplitude parameter).

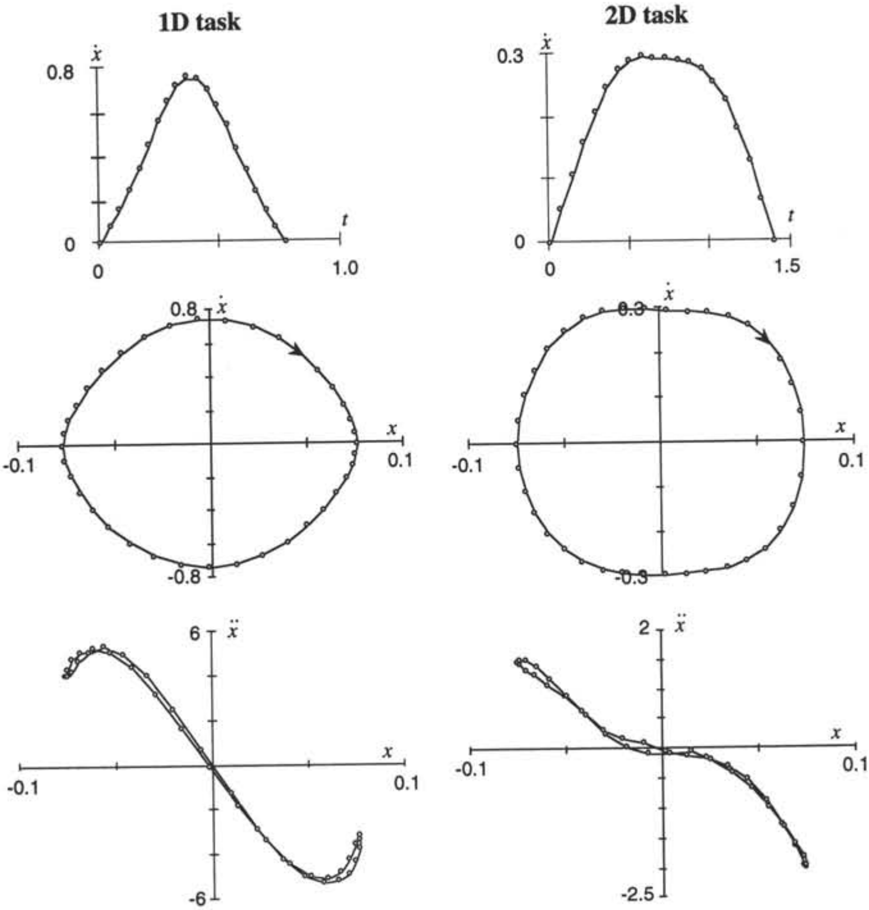

Figure 1: Velocity profile (top) phase portraits (middle) and Hooke's portraits (bottom) of typical normalised average cycle for ID=4, in the 1D experiment (left) and 2D experiment (right). In both experiments, the peak velocity is reached in the first half of the movement with phase portraits slightly skewed to the right. The Hooke's portraits show a softening spring (1D) or a hardening spring (2D) behaviour.

Schöner's (1990) Duffing function can produce both softening and hardening spring behaviour in a limited range of the task space. Thus, this Duffing stiffness description is in agreement with our experimental data. However, for the sake of simplicity, and provided the motion always occurs in a limited range of positions, the quintic Duffing term might be neglected (e.g., Zaal, 1995).

With respect to the emergent kinematics, one major limit of Schöner's model lies in the shape of the predicted speed profiles. The velocity profiles generated by the model are asymmetric with a shorter deceleration phase (leading to a phase portrait skewed to the left) which clearly contradicts our experimental results as well as more classical ones (e.g., MacKenzie et al., 1987). Hence, because the velocity profile asymmetry is a consequence of the dissipative terms, the Van der Pol damping function cannot, by itself, account for the experimental trajectories observed.

To produce asymmetric velocity profiles with a shorter acceleration phase, a structural change, where the Van der Pol dissipative term is replaced by a Rayleigh term, is a solution: The Rayleigh oscillator exhibits very similar dynamic properties (i.e., same Hopf bifurcation) but the dissipation is governed by a peak velocity related parameter (instead of an amplitude related parameter) and produces asymmetric velocity profiles with a shorter acceleration phase. Thus, to model our data, a "velocity driven" Rayleigh dissipative function should be preferred as the main contributor to the limit cycle behaviour.

In order to propose a *minimal* dynamical model for trajectory formation, we found that a cubic stiffness function and a Rayleigh damping function suffice as the basic ingredients. This model can reproduce the main classical human movement categories (i.e., cyclical self-sustained oscillations, point-to-point discrete motion and postural behaviour), while at the same time assuring the asymmetric shape of the velocity profiles. This inclusion of a Rayleigh damping function in a minimal model, has strong consequences for the behavioural information used: because Rayleigh is "velocity driven", this modelisation emphasises the role of velocity related information as primary behavioural information.

One limit of our minimal model is that it cannot account for certain frequency-amplitude and peak velocity-frequency relationships reported which are better predicted by the hybrid model (Kay et al., 1987). However, the hybrid model lacks a non-linear stiffness (to account for discrete movements). Thus, a mixed version of our model and the hybrid model (i.e., Van der Pol + Rayleigh damping and Duffing stiffness) might be preferred at the price of including new parameters in the model.

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Effects of Runway Outline and Ground Texture on the Perception of Time-to-Contact in Simulated Landings

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Abstract

Previous research indicated that pilots use some kind of Time-to-Contact (TTC) strategy to initiate the flare maneuver. In the present experiment it was examined whether addition of ground texture to a simulated visual display of a runway environment would improve the perception of TTC. The results suggest that texture indeed enables a pilot to improve the landing performance due to a better perception of TTC.

Introduction

There is continuous growth in the use of flight simulators for training pilots for difficult tasks, such as landing an aircraft. In order to properly evaluate the pilot's behaviour, it is important that the information presented be as realistic as possible. This is particular true of visual information. As far as fidelity is concerned, it has been assumed that dynamic transformations of scene elements are more important than the scene elements themselves, since these transformations create an optic flow field providing information on egomotion and about the aiming point (Gibson 1979). Additionally, the optic flow field contains information about the Time-to-Contact (TTC, Lee 1980).

Research using the flight simulator of the Delft University of Technology indicated that pilots use TTC for the timing of the moment of initiation of the flare maneuver (Advani et al. 1993). However, the timing of the flare was also related to the height above the ground, corresponding to a certain angular size or optical angle ψ, defined as the angle between the sides of the runway (sideways from the aiming point) and the pilot's eyes. In the latter experiment, simulations were used that represented approaches by night. Hence, the only visible cue was provided by the outline of the runway.

The present experiment was designed to test the hypothesis that addition of ground texture to a visual runway scene would increase the visible optic flow field and thus would improve the perception of TTC as compared with a runway outline only.

Method

The experiment was done by using a Silicon Graphics workstation, showing several synthetic runway scenes in random order (Figure 1):

1. runway outline,
2. ground texture,
3. a combination of runway outline and ground texture.

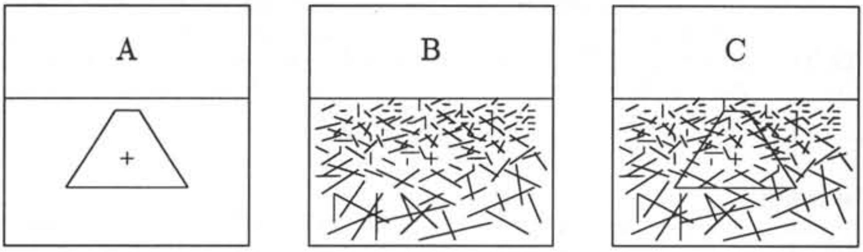

Figure 1. Synthetic runway scenes: A. runway outline, B. ground texture, C. runway outline and ground texture

The scenes were approached along a straight line, using three different approach speeds (V = 50m/s, 60m/s and 70m/s) and two different glide path angles ($\gamma = 2°$ and 4°). The combination of the different values of V and γ resulted in six different sink rates C (i.e. the vertical component of the approach speed), ranging from C = 1.74m/s to C = 4.88m/s. To obtain a smooth landing, the approach had to be succeeded by the flare maneuver. In this experiment the flare was preprogrammed such that an optimal landing would be achieved initiating the flare at TTC = 6 seconds, irrespective of sink rate. To prevent that subjects would trigger the flare at a certain value of the optical angle ψ, which would introduce an artefact in the experiment, two runway widths were used, increasing the number of visual scenes with two.

Seven subjects - without any previous flying experience - participated in the experiment. After several training sessions, every subject completed ten replications of all combinations of runway scenes and sink rates. The subjects were instructed to initiate the flare - by pressing the spacebar - in order to obtain a landing with an optimal touchdown sink rate C_{TD} = 0.33m/s. A landing was considered 'smooth' when the sink rate at touchdown was between 0.05m/s and 0.90m/s. The simulation provided subjects with feedback information of the sink rate at touchdown after each trial.

Data were analyzed by means of a 3 (approach speed) by 2 (glide path angle) by 5 (scene) analysis of variance, using a significance level at $\alpha = 0.05$.

Results and discussion

One may assume that the best perception of TTC would be revealed by a constant TTC-strategy, independent of the approach speed V and the glide path angle γ. In the conditions with visible texture, TTC at onset of the flare maneuver was neither significantly influenced by V nor by γ. It is worth mentioning that there appeared to be no significant difference between the conditions with both an outline and texture and the conditions with texture only. In the conditions with the runway outline as the only visible cue, TTC at onset of the flare was significantly influenced by V, but not by γ. These results are illustrated by the data of one typical subject, which are shown in figure 2. This figure shows representative mean values and standard deviations of TTC at onset of the flare as a function of the sink rate. The upper part of the figure refers to a runway outline only scene, whereas the lower part refers to a scene containing both a runway outline and ground texture. The optical angle ψ at onset of the flare maneuver was

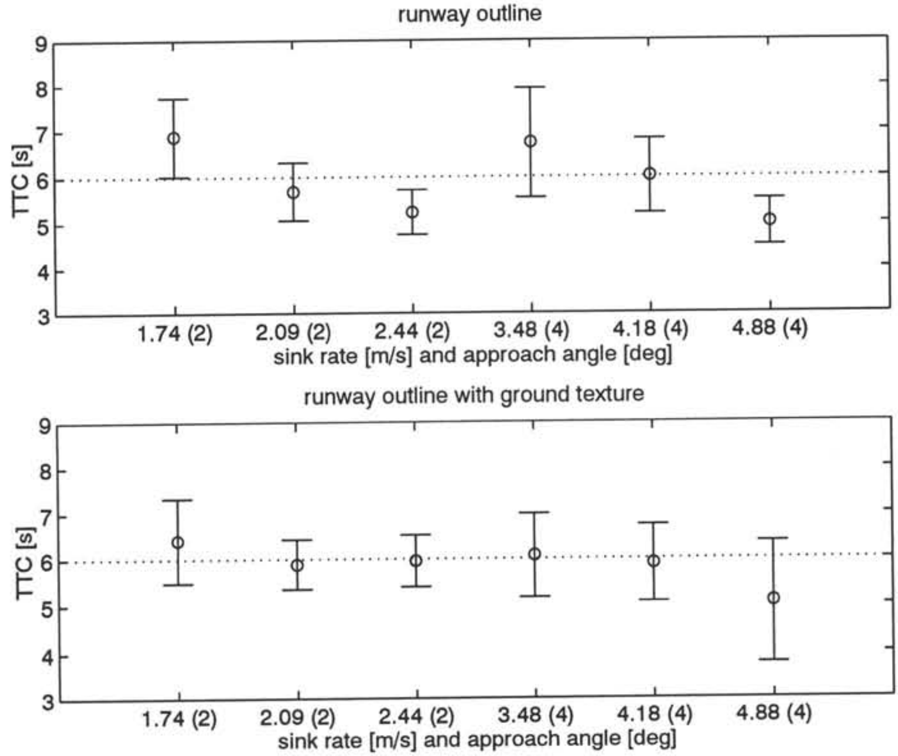

Figure 2. TTC versus sink rate at onset of the flare (results of one subject)

significantly influenced by V when the scenes contained texture. The glide path angle did not have any significant influence on ψ. When the scene only contained a runway outline, ψ was neither significantly influenced by V, nor by γ.

In accordance with the previous, TTC at onset of the flare was not significantly influenced by the runway width when the scene contained texture. Without texture, the runway width did have a significant effect on TTC. Not withstanding our attempt to prevent this phenomenon from occurring, ψ was significantly influenced by the runway width for all scenes containing a runway, irrespective of the presence of texture.

These results indicate that a display showing a runway outline without ground texture provides less accurate information to enable a pilot to initiate the flare on the basis of TTC only, than a display showing ground texture. Instead, subjects seem to prefer for a particular runway a certain value of the optical angle ψ to trigger the flare. However, the results presented by Advani et al. (1993) suggest that in such conditions the initiation of the flare maneuver might as well been based on a combination of values of both ψ and TTC.

In the present experiment, the texturized scenes provided information which enabled subjects to base the onset of the flare almost completely on TTC alone. Further, the presence of a runway outline appears to have no effect at all on the perception of TTC.

Conclusion

Addition of ground texture to a runway scene in a visual simulation was shown to significantly improve the perception of the Time-to-Contact and hence the landing performance. The effect of a runway outline appears to be negligible. In fact, when such an outline is the only visual cue, subjects seem to time the onset of the flare maneuver on the basis of the optical angle ψ.

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The Influence of Stimulus Length on Static Haptic Curvature Discrimination

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Abstract

The influence of stimulus length on static haptic discrimination of curvature was investigated for different placements of the stimulus on the hand. The sensitivity for curvature discrimination does not appear to depend consistently on the region of the hand with which the stimuli are touched. The discrimination thresholds in terms of radius of curvature and in terms of base-to-peak height difference as a function of contact length are shown to increase monotonically. In our experiment, the effective stimulus for discrimination of curved strips is found to be the total change of local surface attitude, a first order variable.

Introduction

In an earlier investigation static haptic discrimination of curved strips from a straight strip was tested for nine different placements of the stimulus on the hand (Pont et al., 1995). The length over which the strips were touched seemed to covary with the discrimination thresholds for the nine different placements. Here we systematically study the influence of the length of the strips, and thus of the contact area, on static haptic discrimination of curvature. Discrimination thresholds for different lengths of the stimuli and different placements of the stimuli on the hand are compared. We investigated whether the sensitivity for curvature discrimination correlates with the part of the hand with which the strips are touched or with the zeroth, first or second order geometrical properties of the stimulus. The latter variables are represented by the base-to-peak height difference, the total change of local surface attitude and curvature respectively.

Method

Stimuli

The stimuli are curved strips with a length of 8 cm or 20 cm, a width of 2 cm, and a base-to-peak height of 5 cm (see figure 1A). We tested how well subjects could discriminate a straight strip from 8 different curved strips with a constant curvature in the range -1.6/m to +1.6/m. The curvature is the reciprocal of the radius of curvature, so a curvature of k=0.2/m is represented by a circle with a radius of (1 / 0.2) m=5 m. All conditions tested are presented schematically in figure 1. In the case of the thumb (placement 5), middle finger (placement 7) and little finger (placement 9) two conditions were tested with strips with a length of 8 cm: in one condition these shapes were touched with the finger only and in the other condition the shapes were touched just with the part of the palm of the hand which is involved in these placements (figure 1B). In placement 1 (figure 1C) one condition was tested in which the subject had to spread the fingers as much as possible. For this placement we also tested a condition in which the subject had touch the strips with the fingers held together (figure 1D). In these two conditions we used strips with a length of 20 cm, because in the "wide" condition the area over which the strips were touched exceeded 8 cm. Figure 1E depicts the nine conditions tested in earlier research (Pont et al., 1995). The results of these experiments are taken into account in the analysis of the results of the present experiment.

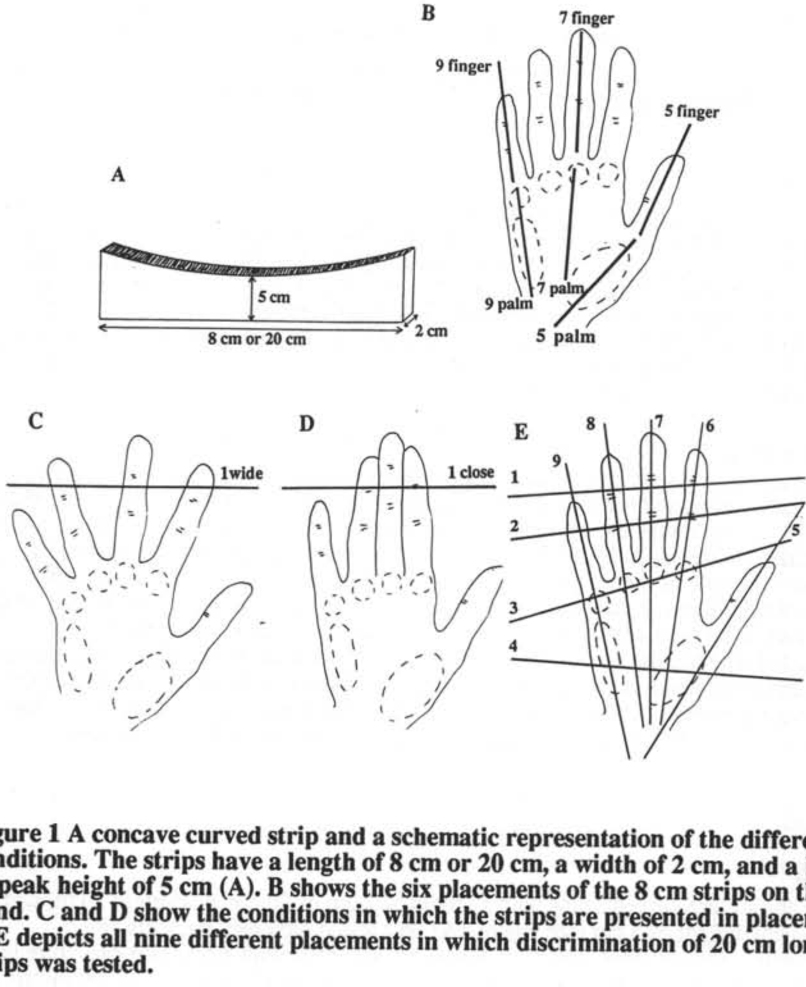

Figure 1 A concave curved strip and a schematic representation of the different conditions. The strips have a length of 8 cm or 20 cm, a width of 2 cm, and a base-to-peak height of 5 cm (A). B shows the six placements of the 8 cm strips on the hand. C and D show the conditions in which the strips are presented in placement 1. E depicts all nine different placements in which discrimination of 20 cm long strips was tested.

Subjects and experimental setup

Three subjects participated in the experiments. Subjects RB and IH were naive and paid, whereas subject SP (not one of the authors) is experienced in haptic experiments. They were seated behind a curtain which prevented them from seeing the experimenter and the stimuli. The subject put the palmar side of his or her right hand under the curtain to touch the stimuli presented by the experimenter.

Procedure

In this experiment a two-alternative forced choice procedure was used. The subjects had to judge by using static touch which of two successively presented stimuli was the more positively curved.

The range in which discrimination was tested differed for the different conditions and subjects and was adjusted after each session, on the basis of the estimations for the thresholds in the previous experiment. We fitted psychometric curves to the percentages of judgements in which the test shape was judged more convex than the reference shape, as a function of curvature. The data points were weighted linearly with the number of trials to which these percentages applied. Sigma represents the steepness of the curve or the discrimination threshold at 84% correct. The bias represents the 50% point.

Results and discussion

None of the biases is significantly different from 0/m, as we expected. For none of the three subjects did we find a consistent variation in the discrimination thresholds as a function of the part of the hand with which the stimuli are touched. Thus apparently, the local structure of the hand is not the main factor determining the curvature discrimination thresholds. For this reason we looked at the data in terms of geometrical properties of the stimuli.

The discrimination thresholds were calculated in units of radius of curvature and in units of the base-to-peak height difference over the contacted area. These values are shown as a function of the length of contact for subjects IH and RB (figure 2). It is perhaps surprising, in view of the differences between the conditions, that these datasets show correlation. For both these datasets and for all three subjects we determined the Spearman Rank-Order correlation coefficients and the level of significance. These values are shown in table I. It is clear that the thresholds in units of radius of curvature and the thresholds in units of base-to-peak height difference show a monotonically increasing relation as a function of contact length. So, models in which discrimination of curvature is based on constant curvature differences or constant height differences (the second and zeroth order structure of the stimulus, respectively) are rejected. However, a model in which the judgements are based on the first order variable cannot be ruled out. In other words, in our experiment the total change of local surface attitude is the effective stimulus for the discrimination of curved strips. This effect was also found by Gordon and Morison (1982) for discrimination and rating of curvature by active touch with the index finger.

In future research, we will study the way in which cutaneous stimulation and kinesthetic stimulation from different parts of the hand integrate in haptic curvature discrimination.

Table I The values of the Spearman rank-order correlation coefficients and significance levels for the three subjects RB, IH and SP for the thresholds in terms of radius of curvature (R) and in terms of height differences (h) as a function of the total length of contact (x).

	R(x)		h(x)	
subject	r_s	P	r_s	P
RB	.822	$7.9\ 10^{-6}$	.463	.023
IH	.488	.017	.856	$1.5\ 10^{-6}$
SP	.625	.002	.821	$8.2\ 10^{-6}$

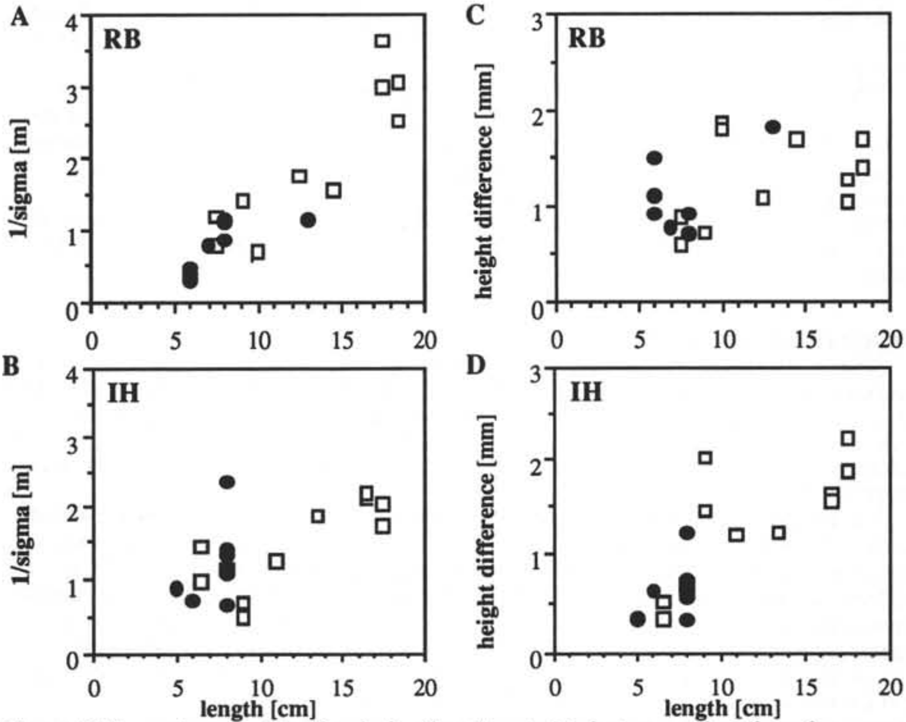

Figure 2 The values for the discrimination thresholds in terms of radius of curvature (A and B) and in terms of base-to peak height difference over the touched part of the stimulus (C and D). The values for all different placements are shown as a function of the total length over which the stimulus was touched in the corresponding positions. Open squares represent the data from the earlier investigation, filled circles indicate the results of the present experiment.

Acknowledgement

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Inconstancy of observer-movement, a perceptual tool?

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Abstract

Interaction is a fashionable label put on a wide range of phenomena. Why would someone want to interact with her environment at all? If personal interaction is not necessary some device might do the job instead. In this respect a tool can be seen as an interface to the outside world, often removing natural forms of interaction, without replacing new forms of interaction.

In our favorite tool, the car, high-tech is setting new standards of locomotion which is highly balanced in speed and heading. This means that the visual information during car driving is smooth. Yet the visual system seems to be well adjusted to the visual information aroused when moving in curly instead of straight paths (De Poot, Bruil and Van de Grind, 1994, Turano and Wang 1994) or moving at inconstant instead of constant speed (Stappers, 1994, De Poot and Van de Grind, 1995). These undulating movements are typical for walking (Stappers, 1992), an old skill, possibly partly mastered through evolutionary experience (Bril, 1996) giving it practical advance over modern skills.

Here a proof is given that observation during biological, namely inconstant, locomotion leaves room to pick up more information from the environment, than modern car driving, giving it a theoretical advantage. This advantage concerns the identification, the localization and interpretation of moving objects in the environment. Experimental results are presented of cases in which observers can effectively interpret the object motion information by active vision. A 'back to the nature' might eventually apply to the visuals during car driving. Promising visualization techniques are presented.

Introduction

It is known that interaction with (active exploration of) the environment allows to pick up information from the environment. Therefore devices have been invented that utilize interaction to allow exploratory sensory perception of simulated or distant realities (virtual reality and teleoperation), especially interactive visual displays responding to the observer's manipulations within a few tens of milliseconds. These systems can be useful for design purposes, but they have also been used for visualization of three-dimensional structures and have been used in vision research. (e.g. Overbeeke and Strattman, 1988, Van Damme and Van de Grind, 1993). A nice low-tech device for active visualization of a static structure is the 'self-statue' mirror (fig 1) specially invented for this presentation in which the viewer can actively pursue her frozen face. The psychological consequences of this deserve to be discussed separately.

For unoccluded static environments the first move an observer makes, arouses already all information available through active vision, namely the depth structure and scale of the environment. (De Poot, 1995, p.7). So in static environments different observer movements arouse similar information. If interactive visual displays visualize *dynamic environments*, different observer movements arouse different, not predictable, information, explained in the theoretical section.

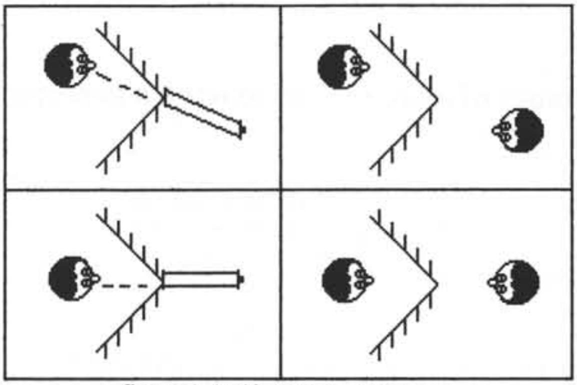

figure 1. 'self-statue' mirror

Theory

Observer movement that is not constant has a potency to arouse information about object motion which is not aroused when not moving or moving only at a constant speed. Of course this is only possible if the environment observed has some structure over time. Like some rigidity of transformations is required for the structure-from-motion percept, the motion-from-motion percept might require motion constancy, i.e., object translations and object rotations remain unaltered over a short range of time.

Stimuli have been designed according to the requirements above, that neither any static perspective, nor any dynamic perspective consisting only of constant observer movement will arouse sufficient information about object motion. All static perspectives an observer can choose from give equivalent visual information and so does constant observer movement in principle (Constant observer-movement which happens to compensate object motion entirely is an exception to this, because object motion and observer-movement are identical then) .

For a laterally moving observer, frontoparallel object rotations about a vertical axis have these properties. Also parallel horizontal object motions at different depths have these properties unless they cross the observer's range of viewpoints. We used object rotations for our experiments. It can be shown that the visual motion of these object-rotations can leave the observer uncertain about the location of the rotation axis (for short lifetimes of the visual elements), the depth order (rotation direction) and the depth scaling (ratio of depth range and frontoparallel range, for a constant visual motion inversely proportional to angular velocity). Even if the observer moves at a constant speed, those quantities will remain unidentifiable in principle. So if active vision is of any use this will be because of the variability of observer movement.

Now the difference between active vision of object motion and active vision of object structure is clear: Uniform observer-movement is sufficient to arouse the motion parallax necessary for structure from motion percept but insufficient to arouse all visual motion necessary for the motion from motion percept.

The stimuli of rotating objects fit our questions: does (variable) observer movement help monocular human observers to interpret object motion and do moving observers make silent assumptions about the constancy of object motion when interpreting object motion? In two experiments we compared monocular perception of object rotations from a static perspective (passive vision) and from a (non uniformly) moving perspective (active vision). Objects were close to the observer, so observer movement easily had a visible influence on the visual motion. In these experiments the interpretation of rotation direction and of angular velocity were compared respectively.

Experimental results

These results have been presented earlier in [De Poot, 1995].

In the first experiment rotating objects of variable sizes and variable transparency were shown of which the rotation directions had to be compared. The results of this experiment show that for even rather large (11 deg) and rather opaque (50%) object discrimination between opposite directions is not accurate for passive monocular observation. For passive observation full depth reversals occur as well as half depth reversals with all visual motion seen at the back of a transparent object or all visual motion seen at the front of an opaque object. For active observation these illusions do not occur and accurate discrimination between opposite rotation directions is possible even for very small very transparent objects.

In the second experiment rotating objects differing in size were shown of which the angular velocities had to be compared. They were partly covered by a mask, so that the object size was not directly visible. The results of this experiment show that for passive monocular observation the discrimination of angular velocities is inaccurate when the objects are partly masked. For an average aperture size of 1/2 object diameter and a ratio between the largest and the smallest diameter of 3 the just (67%) noticeable angular velocity difference is 30%. For smaller relative apertures and wider relative ranges of object sizes the just noticeable difference increases (the accuracy is even worse). For passive monocular observation of partly masked objects the so called short current illusion occurs which makes it appear that a smaller object is entirely visible instead of a partly visible object. For active perception this illusion does not occur and the just noticeable angular velocity difference is rather accurate at 15% irrespective of the relative aperture size and the relative range of object sizes.

Implications for traffic situations

From these experiments we can conclude that active perception by variable observer movement leads to better perception of certain classes of object motion than passive perception (or active perception at a constant speed). For this reason it seems promising to investigate whether there is a relation between the illusions occurring in the object rotations in the experiments above and the illusions that might occur in other forms of object motion: active vision by variable observer movement might have a positive effect in those cases too.

Indeed the metameries occurring in rotating objects have their counterparts in translatory object motion. For any translatory motion the component in the direction of observer movement may be confused with the observer movement induced visual motion component which is added to it. The component in the direction of the observer will not be directly visible at all unless the object's visible size allows interpretation of the expansion component, better known as *tau*. Only the motion component orthogonal to both the observer movement direction and the observer direction is visible and cannot be confused with observer movement induced motion. So there are again two classes of metameries: those referring to the observer directed motion component (cf. the rotation direction) and those referring to the location in depth of motion (cf. the angular velocity).

One might wonder why there is so little confusion visible in practice. This might just be a lack of investigation of the subject. To show this we translate the limitations in object motion perception to the well-known field of traffic situations. A car driver rides at a stable speed in a constant direction for much of the driving time. During those periods the driver may be victim of the above-mentioned illusions.

In many cases additional information about the distance of objects is available in the visibility of the ground plane and other cues. Yet there are traffic situations in which the distance is badly visible so that the above mentioned illusions can occur: at night, at crossings, on curly or hilly, or oppositely very straight and flat roads, in multilayered fly-overs, along railroads, in exceptional weather conditions with extraordinary clear or bad sight, the distance, speed and direction of phenomena may be erroneously estimated. So for traffic situations there is room for additional active vision techniques to enhance the perception of motion and location of other vehicles (object motion) which risk to be (partly) confused with observer motion.

Although capricious car driving can induce a wealth of visual information unavailable to the stable driver, we rather think of active vision techniques which pose no extra constraints on car driving but which take the role of an additional window on the environment. A static mirror provides the car driver with an additional view from an alternative viewpoint. Through a pair of *moving* mirrors the additional virtual viewpoint can be moving in any wanted direction over any wanted range (within the limits of the car-roof and the laws of optics).

Two generic forms of additional dynamic perspective might be the virtual pigeon view and the virtual surfer's view. The pigeon view works like a pigeon head when the pigeon walks: Half of the time the head moves back thus decelerating the visual consequences of body movement, half of the time the head moves forward thus accelerating the consequences of body movement. The resulting acceleration/deceleration is a possible tool for vision, which can in theory recover the distance of moving visual elements and their velocity component in the observer movement direction.

In the surfer's view the head moves laterally as in the object rotation perception study whereas the car moves forward. A nicely interpretable view is created when the surfer fixates at a chosen distance ahead, for instance hundred meters ahead. By doing so the visible environment is covered by dynamic viewpoints from various movement directions. Like the pigeon view the resulting surfer's view is a possible tool for vision, which can in theory recover similar information.

As the movement undulations during walking are in three dimensions (Stappers, 1992) human observers may profit from both visualization tools.

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The Changing-Loudness Aftereffect and Dynamic Spatial Perception

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Abstract

Changing-loudness aftereffects (CLA) may reflect sensory processes concerned with dynamic spatial perception. This is supported by an experiment demonstrating that the spectrally-dependent component of CLA has low interotic transfer: in a single-interval forced-choice procedure, three subjects responded to test stimuli under monotic (same ear for adaptation and testing), interotic (one ear adapted, the other ear tested) and baseline (no adaptation, one ear tested) conditions. In addition, baseline data indicate a perceptual asymmetry, which may be attributable to the percussive nature of many natural sounds.

Introduction

Listening to decreasing intensity in a tone leads to illusory increasing loudness afterwards (Figure 1), while listening to increasing intensity leads to illusory decreasing loudness afterwards (Reinhardt-Rutland, 1980; Reinhardt-Rutland & Anstis, 1982). These changing-loudness aftereffects (CLA) consist of a spectrally-independent component - attributable to response bias - and a spectrally-dependent component - attributable to sensory processing (Reinhardt-Rutland, 1995): spectral dependence characterises early stages of the auditory pathway (Mills & Schmiedt, 1983). The spectrally-dependent CLA component might concern dynamic spatial perception, since dichotic difference in changing intensity is important in dynamic spatial perception (Rosenblum, Carello, & Pastore, 1987); micro-electrode data (Gersuni & Vartanyan, 1973; Stumpf, Toronchuk, & Cynader, 1992) and aftereffects due to horizontal auditory motion (Ehrenstein, 1994; Grantham, 1992) are also consistent with this argument.

This proposed role for CLA requires that the spectrally-dependent CLA component has low interaural transfer, since interaural differences in changing intensity would need to be preserved; this prompts the present study.

Method

Stimuli were based on the multiplication of outputs from Tektronix FG501 and Marconi 2021 function generators, and presented via a Keletron KSA 1500 Mk.II amplifier and Koss ESP6a headphones. Adapting stimuli decreased in intensity at -18 dB per s; this would become inaudible after a few seconds, so adapting stimuli were maintained at a mean of 40 dB SPL by rapid increase of intensity after every

2 s. Each rapid change took 0.2 ms and was heard as atonal.

Test stimuli were derived from adapting stimuli by exploiting a voltage-controlled facility on the Marconi function generator. Of 1.5 s duration, they always started at 40 dB SPL and steadily increased, decreased, or remained constant in sound level. The carriers for adapting and test stimuli were sinsusoidal, of frequency 1 kHz (adapting stimuli) and between 0.5 and 2.0 kHz (test stimuli). Conditions were monotic (adaptation and testing at the same ear), interotic (adaptation at one ear, testing at the other ear) and baseline (no adaptation, testing at one ear).

Subjects - two females and one male with hearing sensitivity within usual limits - adapted for 2 min, heard a test stimulus, adapted for 10 s to maintain adaptation level, tested again, and so on. Each test stimulus required a forced binary response of "growing louder" or "growing softer". During preliminary sessions, test stimuli were selected for each subject's experimental sessions, with and without adaptation. The subject responded to seventeen test stimuli in random order, with rates of change of between +8 and -8 dB per s in 1 dB per s steps; previous research suggests that CLA nulls lie well within this range (Reinhardt-Rutland, 1980). From these responses, five stimuli were selected as being around the subject's null, that value of test stimulus for which equal numbers of "growing louder" and "growing softer" responses would be elicited. In the main part of the experiment, these stimuli were each presented a total of eight times in random sequence, four times to each ear in different experimental sessions.

Nulls were computed from each set of forty responses by applying Engen's (1971) technique for dealing with single-interval forced-choice data. This assumes approximately ogival patterns of responses, which applied to the present results. The proportions of a given response - "growing louder" responses were chosen - for each set of test stimuli were transformed into standard scores to linearize their distribution: the null corresponded to a standard score of zero.

Conclusions

In Figure 2, monotic and interotic nulls can be compared with baseline nulls to indicate the nature of CLA in these conditions. Interotic nulls indicate a little CLA at most test frequencies; there is little evidence of peaking at the 1 kHz test frequency, indicating spectral independence. Monotic data also indicate a little CLA at test frequencies away from 1 kHz, presumably due to spectrally-independent aftereffects in these cases. However, there is clear peaking of CLA at 1 kHz. This suggests that, while the spectrally-independent component of CLA may have high interaural transfer, the spectrally-dependent component of CLA has low interaural transfer. This is consistent with the proposed role of the latter in dynamic spatial perception. Results of an ANOVA (test frequency X adapting condition) were significant for both factors.

Another point to emerge from the data is that perceived steadiness of unadapted test stimuli requires that they diminish in intensity. Related asymmetries have been reported elsewhere (Arlinger & Jerlvall, 1979; Small, 1977). They probably reflect the rarity of steady stimuli outside the laboratory; many natural sounds are percussive, with rapid rise and slow decay.

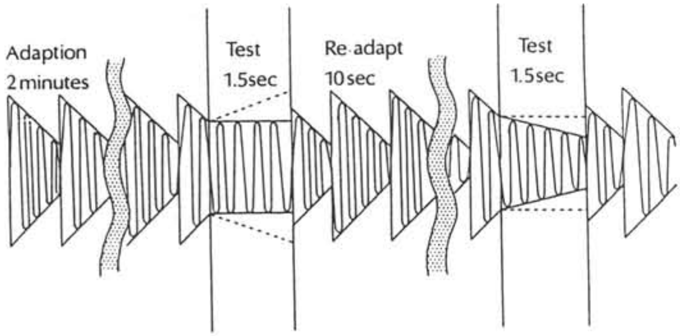

Figure 1. Schematic representation of decreasing intensity adaptation leading to increasing-loudness CLA. In the test stimulus on the left, sound level is steady but the stimulus is heard to get louder (represented by broken lines). CLA is nulled in the test stimulus on the right, so it is heard as steady.

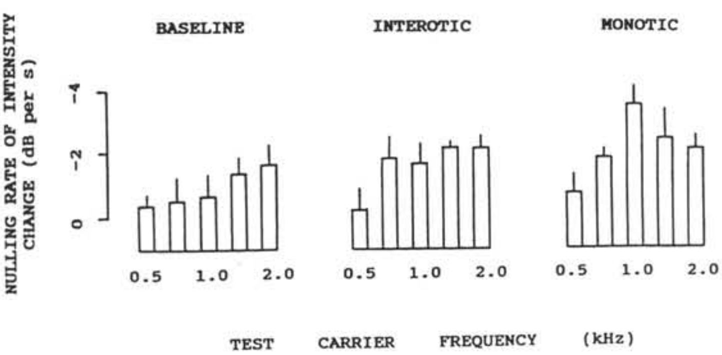

Figure 2. Combined results for three subjects, showing mean and SE of nulls in the the three conditions.

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Velocity Transposition in Motion Extrapolation: Some Implications for the Relation between Perception and Action

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Abstract

How does velocity transposition relate to motion extrapolation? A small or large object (two dots horizontally separated by either 0.2 or 0.8°) moved at constant speed within a 10- or 2.5°-rectangular aperture, and then was occluded. Ss pressed a key when they thought the hidden object had reached a randomly specified position (0-12°). For both apertures, in agreement with the transposition principle, extrapolation response time was found to be longer for the large moving object than for the small. However, contrary to conventional predictions, extrapolation time increased with the shorter apertures regardless of the moving-object size. The findings suggest that the visual system performs, according to the transposition principle, a spatiotemporal scaling of motion across visible and occluded spatial settings which then "directly" (monotonically) relates to the timing of extrapolated motion.

Introduction

The classic velocity-transposition principle - the larger the moving object and/or its framework, the slower its perceived velocity (see Brown, 1931a; Mack, 1986), - has been shown (Sokolov, Ehrenstein & Pavlova, 1995) to apply to extrapolation of translatory motion, i.e., observers respond more slowly to a large than to a small occluded objects that, while visible, moved at moderate or fast velocity. According to the transposition principle, the spatial framework, i.e., the size of aperture, through which motion is observed (in addition to the moving-object size) may also affect response time for extrapolated motion. If this prediction is correct, the reduction of visible motion path (and moving-object size) would result in faster perceived velocity, and, hence, in shorter response time. The present experiment was designed (a) to examine the effect of aperture size on motion extrapolation, (b) to test the moving-object size effect for short apertures, and (c) to establish whether combined effects of both moving-object and aperture size occur.

Method

The experiment comprised two sessions that differed only with respect to the length of visible-motion path as defined by the aperture size. The same six subjects (two women and four men with normal or corrected-to-normal vision, naive as to the aim of the study) participated in both experimental sessions. They were to estimate time-to-arrival (T_a) of objects that moved horizontally (left-to-right) at constant speed (5°/s) in a frontoparallel plane within "long"(10°; Session 1) or "short" (2.5°; Session 2) aperture against otherwise grey background. Two rows of white strips were attached above and below the apertures with separations 1° between individual stripes horizontally, and 0.5° between the rows of stripes vertically.

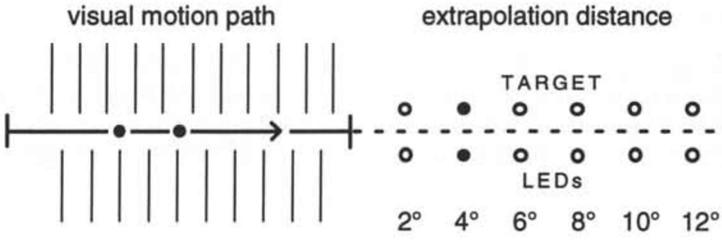

Figure 1 A schematic representation of the experimental setup.

Stimuli were horizontally oriented pairs of light dots with either 0.2° ("small" object) or 0.8° ("large" object) separation. Ss pursued the object (i.e., the light-dot pair) binocularly at a distance of 57 cm until it disappeared behind a nontransparent screen, and pressed a key at the moment the leading edge of the occluded moving object would reach one of seven randomly specified positions (ranging from 0-12°) marked by a vertical pair of red LEDs. A scheme of the experimental setup is shown in Figure 1.

Results

The results of both sessions are depicted in Figure 2. It shows the mean absolute error in extrapolation (response) time, i.e., the difference between averaged-across-observers

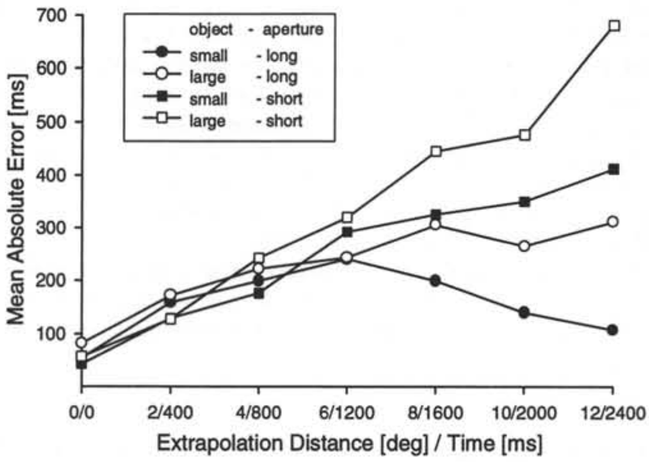

Figure 2 Mean absolute errors in response time to extrapolated motion [T_r - T_a] across different extrapolation distances (0-12°) for small (0.2°) and large (0.8°) objects that, while visible, moved within long (10°) or short (2.5°) aperture. The greater the mean absolute error, the greater the respective response time. Each experimental point is an average of 72 measurements.

response time (T_r) to a given moving object and its physical arrival time (T_a). The data indicate that irrespective of the visible motion path, (1) T_r is systematically shorter for *small* than for *large* moving objects ($p < 0.01$); (2) the mean difference of respective T_r for the two objects increases with extrapolation distance ($p < 0.02$). However, contrary to the velocity-transposition predictions, reduction of the aperture for visible motion in general increases the response time for occluded motion, i.e., (3) for equal-sized objects, T_r is significantly longer when visible motion occurred within *short* as compared to *long* apertures ($p < 0.01$); furthermore, (4) it tends to be longer for *small* object moving while visible within *short* aperture than for *large* object and *long* aperture ($p < 0.08$). Finally, (5) T_r is significantly longer for *large* object moving while visible within *short* aperture than for *small* object and *long* aperture ($p < 0.002$).

Discussion

The present experimental results partially confirm our earlier findings (Sokolov et al., 1995) and expectations based on the velocity-transposition principle: following either short or long aperture, observers respond faster to small than to large occluded moving objects.

However, most other findings seem to contrast the conventional velocity-transposition predictions. It appears that if the perceived-velocity transposition and "direct" perception-action coupling do occur, the *shortening* of the aperture and the moving-object size would *speed up* the observer's response to occluded motion. Yet, in the present study, those manipulations are found to delay the response times (see Figure 2). The results may be explained in a number of ways including rejection of the transposition principle in favour of a specific coupling between motion perception and response to occluded motion. The latter, however, would still fail to account for all our findings on motion extrapolation.

A more comprehensive account suggests that the visual system does accomplish a spatiotemporal scaling of visible motion according to the transposition principle (see Zohary & Sittig, 1993). Moreover, it implies (1) the same scaling algorithm for extrapolated motion, (2) "direct" (monotonic) mapping of scaled temporal characteristics of perceived motion onto response time for occluded motion, and (3) a distinction between a time-unit (the time needed for an object to traverse a unit of space) and a cumulative time (the time needed to cover equal spaces),- see also Brown (1931b, p. 241).

Thus, according to the velocity transposition, the shorter the aperture for object motion, the greater its perceived velocity should be. This means that within a short aperture, the object traverses perceptually the same distance in a shorter time, i.e., the time-unit is finer as compared to long aperture. And inversely, the object appears to cover the same physical viewing- or extrapolation distance for a longer cumulative time. This cumulative time comprises *more* such fine time-units following short aperture, and *fewer* coarse time-units following long aperture. Otherwise, in the former case, physically equal extrapolation distance is perceptually longer (see Reynolds, 1968) and so is the extrapolation (response) time (see *Results*, (3), and Figure 2). The same reasoning is well applicable to account for the two present findings when the size of both aperture and moving object is proportionally reduced (see *Results*, (4)) and when it changes in the opposite directions (5),- see Figure 2.

If we consider again the two different-sized objects moving while visible within the same aperture, consistent with the velocity-transposition principle, the small object (0.2°)

was found to be typically perceived to move at a greater speed. Again, this means it covers physically equal viewing (and extrapolation) distance for a shorter cumulative time. In other words, physically the same viewing- and extrapolation distances *appear* shorter, and observers extrapolate motion of small as compared to large object with a shorter response latency (Figure 2; see also Sokolov et al., 1995). Clearly, errors of measurement tend to sum up linearly with increasing distance. This simple arithmetical consideration might explain a linear increase of differences in respective response times across extrapolation distances found in the present and some related studies (see Figure 2). Thus, additional cognitive explanations become unnecessary. The present account has implications also for understanding the perception of visual motion, namely, for differences in perceived velocity that are modulated by spatial properties of moving object and its framework, the issue which appeared paradoxical for Brown (1931c).

In conclusion, the present findings and their interpretation point to remarkable similarities that exist between modal and amodal perception in the sense of Michotte (see Thines, Costall & Butterworth, 1991). The velocity-transposition principle can be applied to both motion perception and motion extrapolation that afford the perceptual information to guide action.

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The Influence of Eccentricity on the Indication of the Singular Point in Rotating Flow Fields

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Abstract

We investigate how well subjects can indicate the singular point (the point with zero speed) in a rotating flow field, and whether performance depends on eccentricity. Our stimuli consist of rotating random dot patterns. Veridicality and reproducibility are found to decrease with increasing eccentricity of the entire stimulus window. Effects of the location of the singular point within the same stimulus window are small.

Introduction

Gibson (1950) first acknowledged the fact that the optical flow field contains information that is very important for our navigation through the world around us. Koenderink (1986) has shown that this optical flow field can be decomposed (in first-order) into four invariant components: expansion/contraction, rotation, dilation and pure shear. Gibson (1950) and others have suggested that the "focus of outflow" would be very useful to subjects for retrieving information about their heading direction. This "focus of outflow" coincides with the singular point (the point with zero speed) in an expanding stimulus. However, such a singular point is present in all first-order optical flow fields. This brings us to a very interesting question: How well can subjects determine the location of this singular point.

In our experiment, subjects had to indicate the singular point in a rotating flow field with the cursor. In this case, we chose a rotating flow field, but in experiments with similar stimuli (te Pas et al., 1994; 1996) we have shown that there is no difference between the thresholds for rotating and expanding stimuli. Therefore, we feel that any conclusions that are reached here can be extended to include expansions. We vary the eccentricity of the stimulus window, and the location of the singular point within that window. Experiments performed by other researchers (e.g. Warren et al., 1988) have yielded 75% correct thresholds for the discrimination of heading direction. These thresholds are of the order of magnitude of 1°. If subjects use the singular point to retrieve their heading direction, we would expect thresholds for the determination of heading direction to be similar to thresholds for the indication of the singular point.

Method

Apparatus and Stimuli

Experiments are conducted on a MacIntosh Quadra 800 computer with an Apple 19" grayscale monitor. The stimulus window is circular with a diameter of 20° of visual angle. We use pseudo-random dot patterns, consisting of 200 dark dots (5x5 pixels) on a light background. Moving patterns are generated by presenting sequences of frames stroboscopically. In between two consecutive frames all dots "move with the flow". Four subjects participated in the experiments, two of the authors (SP and HO) and two others (GK and TP). GK and TP are paid subjects who were unaware of the purpose of the experiments. All subjects had normal or corrected to normal vision.

The stimulus movement is a curl (clockwise or counter-clockwise rotation). The value of the curl is always 4 rad/s over the entire stimulus area. In an experimental session we vary the location of the singular point (the "centre" of the flow field, where the speed is zero). An example of our stimulus is shown in Fig. 1.

Procedure and Data Processing

In each session we present the stimulus centre at a different eccentricity: one session in the fovea: (0, 0), two in the upper visual field: (0, 10) and (0, 20), and two in the nasal visual field: (-10, 0) and (-20, 0). The stimulus was always located in the centre of the screen; we vary the location of the fixation cross. Within one session the eccentricity of the stimulus is kept constant. The only variable is the location of the singular point.

A typical trial proceeds as follows: A fixation cross appears about 0.5 sec before the stimulus. This fixation cross remains visible throughout the trial. Then the stimulus appears. Subjects have to indicate the location of the singular point with the cursor. The stimulus remains visible until the subject presses the mouse button to indicate that they think that the cursor is at the location of the singular point. Then the next trial starts. During an experimental session, each of the 20 different singular points is presented 30 times in random order. Thus, we obtain a cloud of answers for each location. We chose an indication task because the cloud of answers from the subject gives us both the size and the direction of a possible deviation from the veridical. A two-dimensional measure of the reproducibility is also available.

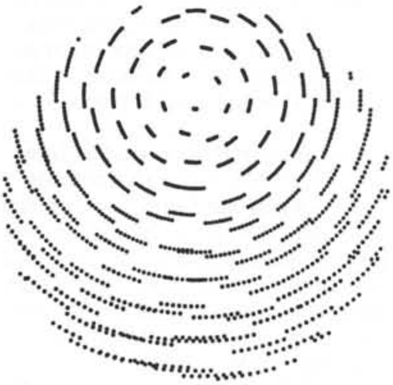

Figure 1: An example of our stimulus. Here the 16 different frames are superimposed to create a static image of our dynamic stimulus.

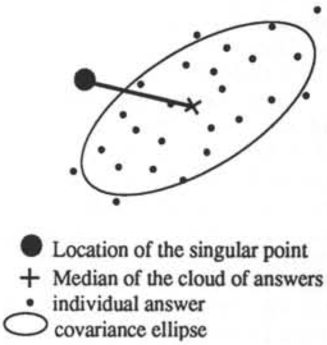

Figure 2: Schematic representation of one of the singular points, the median, the covariance ellipse and the cloud of answers that was given by the subject.

Firstly, we calculate the median location of the cloud of answers. If there were infinitely many data points, we could calculate the 1D-median for every direction, and integrate over all directions. However, with a limited amount of data points this makes no sense. Therefore, we take the 1D-median of the projections of the data points in three different directions (0 deg, 60 deg and 120 deg), and we average these three values to derive a 2D-median. The location of the median provides information about the direction and the amount of deviation from the singular point that was actually presented.

Secondly, we compute the covariance matrix of the data. We derive a covariance ellipse from this matrix by extracting its Eigenvalues. These Eigenvalues, together with their corresponding Eigenvectors, give us length and direction of the minor and major axes of the covariance ellipse. The covariance ellipse gives us an impression of the reproducibility of the data in all directions. Furthermore, it determines whether the deviation from the veridical point is significant or not.

The singular point that was presented, the cloud of answers, its median and the covariance ellipse are depicted schematically in Fig. 2. In the rest of this paper we will not show all the individual data points. Instead we will present the covariance ellipse and the median for every location of the singular point.

Results

Fig. 3 shows the medians of the cloud of answers and the covariance ellipses for subject GK. Sessions at different eccentricities are combined to present an overall picture. Results for other subjects are comparable, although there are differences between individual subjects in the size of the ellipses and the deviations.

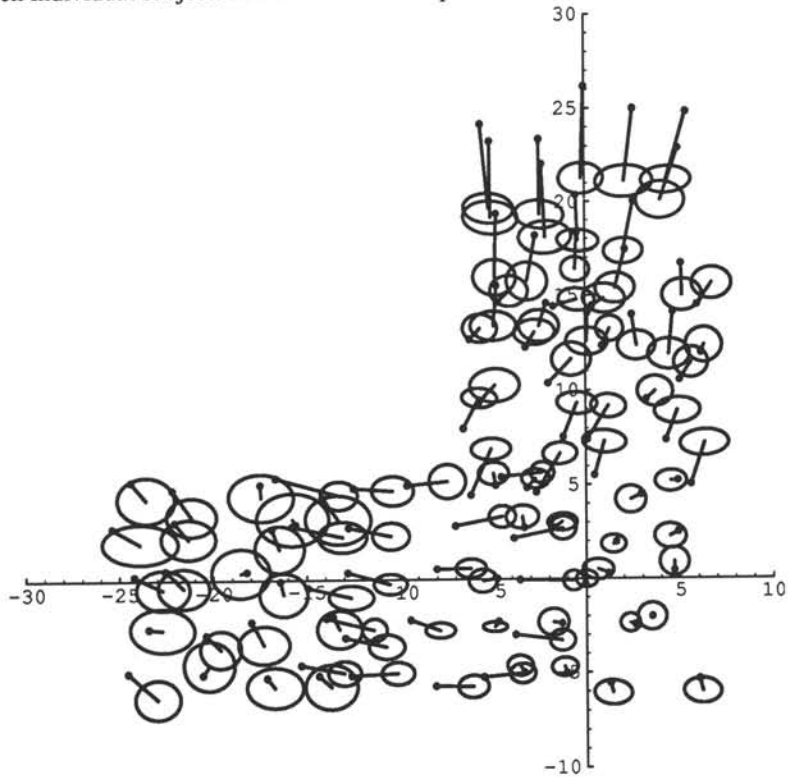

Figure 3: Results for subject GK. The dots indicate the location of the singular point that was presented. The lines connect this singular point to the median of the cloud of answers that the subject gave. The ellipses are covariance ellipses of the cloud of answers.

A striking result is that there is an anisotropy between the upper and the nasal visual fields. Deviations from veridical are much larger when the stimulus was located in the upper visual field than when it was located in the nasal visual field, especially at 20° of visual angle.

In the overall graph, we can observe differences in the results obtained for the five different sessions. The location of the stimulus window obviously influences performance. An increase in eccentricity of the stimulus window results in a decrease in reproducibility (larger ellipses) and a decrease in veridicality (a larger distance between the median and the actual position of the singular point). Within one session, however, variations are small.

Discussion

The deviations from the veridical which we find for the foveal stimulus are of the same order of magnitude as those reported by Warren et al. (1988). In their experiment, subjects had to discriminate the direction of heading (to the left or to the right of a marker). Nothing was asked about the singular point. The fact that our results are similar to those of Warren et al. (1988), despite the totally different paradigm and question, suggests that the singular point is indeed very important for the discrimination of heading direction.

We found a marked anisotropy between the upper and the nasal visual field: deviations from the veridical are much larger in the upper visual field than they are in the nasal visual field. Such anisotropies have been reported before for other stimuli (van de Grind et al., 1993). Both reproducibility and deviation from the veridical increase with increasing eccentricity of the stimulus. However, effects of eccentricity within one stimulus window are small. This might be due to the limited size of the stimulus window (20°). Alternatively, the amount of foveal information might be crucial. Experiments using stimuli with different field sizes might shed some light on this question.

Acknowledgement

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The Visual Perception of 3D Shape

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Abstract

Observer sensitivity was measured for various aspects of local 3D structure on smoothly curved surfaces defined by shading, texture, motion, and binocular disparity. In one set of studies observers were required to judge whether the difference in depth or orientation between the two designated probe regions on a smoothly curved surface was greater or less than a predefined standard. In other experiments, observers performed adjustment tasks to match the local structure at designated points on a visible surface. The results reveal that our perceptions of local depth or orientation are surprisingly inaccurate and unreliable, and that both types of judgment exhibit large failures of constancy over changes in viewing distance, surface reflectance, or the pattern of illumination. Such findings suggest that our perceptual awareness of environmental stability cannot be based on a perceptual representation of local metric depth or orientation as is commonly assumed in many theoretical analyses of 3D form perception.

Introduction

One of the most perplexing phenomena in the study of human vision is the ability of observers to perceive the 3D layout of the environment from patterns of light that project onto the retina. There are many different aspects of optical stimulation, such as shading, texture, motion and binocular disparity, that are known to provide perceptually salient information about 3D structure, but an effective computational analysis of this information has proven to be surprisingly elusive. One possible reason for this, I suspect, is that there has been relatively little research to identify the specific aspects of an object's structure that form the primitive components of an observer's perceptual knowledge. After all, in order to compute shape, it is first necessary to define what "shape" is.

Consider, for example, the stereogram of a smoothly curved surface presented in Figure 1. Clearly there is sufficient information in these images to produce a compelling impression of 3D form, but what precisely do we know about a depicted object that defines the basis of our perceptual representations. Almost all existing theoretical models for computing the 3D structures of arbitrary surfaces from shading, texture, motion or binocular disparity are designed to generate a particular form of data structure that we will refer to generically as a *local property map*. The basic idea is quite simple and powerful. A visual scene is broken up into a matrix of small local neighborhoods, each of which is characterized by a number (or a set of numbers) to represent some particular local aspect of 3D structure. The most common form of this representation in analyses of motion or stereo is a depth map that encodes the distance from each local neighborhood to the point of observation, though it is also common to use local orientation maps, especially in the analysis of shading and texture (e.g., see Marr, 1982).

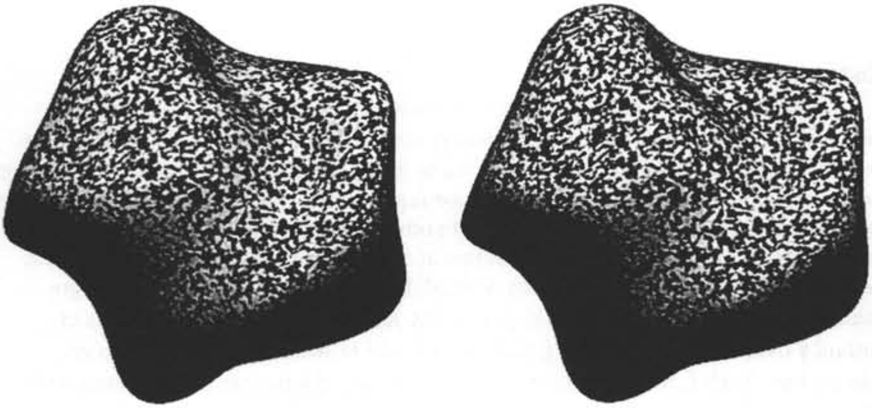

Figure 1 -- An example stereogram similar to those used by Norman and Todd (1996) to investigate observers' judgments of local depth and orientation

An Inventory of Local Surface Properties

There are many possible local properties of a surface that could potentially be used for its perceptual representation, and it is useful to consider two general factors by which they can be distinguished. One of these factors involves varying levels of differential structure. For example, a depth map represents the zero order structure of a surface. By successively differentiating the pattern of depths it is possible to compute successively higher levels of differential structure, such as local orientation or curvature. The other important factor to consider is that most local properties can only be defined relative to some external frame of reference (i.e., a coordinate system), whose component dimensions are represented as independent entities. Thus, for a given level of differential structure, there is a different set of component properties for each possible coordinate system.

Position -- As I indicated above, the most commonly used property for identifying a particular a point in space is its position. For most models of 3D form perception that represent objects using a local position map, the origin of visual space is located at the observer's point of observation, and the positions of all other points are defined by their distances from the origin along the line of sight and in the horizontal and vertical directions of the frontoparallel plane. Although this is a convenient form of representation for many perceptual tasks, there are other possible frames of reference that are sometimes employed in special-case situations. For example, with certain types of objects such as the human body that have well defined axes of symmetry, it is useful to represent local positions in an object centered space where the principal directions are defined by the axes of symmetry.

Orientation -- The property of surface orientation is defined by the gradient of surface depth in each local region, or alternatively, by the direction of a line that is perpendicular to the surface at its point of intersection. In order to represent surface orientation, it is also necessary to adopt an appropriate frame of reference. Usually this is defined by the observer's line of sight. The angle between the surface normal and the line of sight is often referred to as *slant*, and the angle of its projection in the frontoparallel plane with respect to vertical is referred to as *tilt*.

Curvature -- The property of surface curvature is defined as the rate at which orientation changes in any given direction along a smoothly curved surface. In general, the curvatures at a particular location will vary in different directions, with a maximum value in one direction and a minimum value in the orthogonal direction. These are referred to as the *principal curvatures* -- or k1 and k2. The total curvature can be represented as a point in a Cartesian space where k1 and k2 are plotted along orthogonal axes. Alternatively, it is also possible to transform this space using polar coordinates, where the radial and angular components are referred to respectively as the *curvedness* and *shape index* (Koenderink, 1990). An important property of this latter representation is that curvedness varies with object size, whereas the shape index component does not. Thus, a point on a large sphere would have a different curvedness than would a point on a small sphere, but they would both have the same shape index.

Category membership -- Another class of properties that can be used to describe a small local surface region includes the higher-level categories to which it belongs. Many natural objects can be decomposed into a hierarchy of distinct parts. For example, the parts of the human body include the arms, the legs, the torso and the head, and the parts of the head include the eyes, the ears, the nose and the chin. When we wish to describe verbally a particular local region on an object, it is usually more convenient to identify a particular part than to specify a set of coordinates. Thus, my wife might inform me that I have a spot on the lapel of my jacket, or a smudge on the tip my nose. These qualitative labels must also be considered as potential primitives for the perceptual representation of 3D form. Indeed, some researchers have argued they may be of greater importance than are the metrical properties of position, orientation or curvature (e.g., see Biederman, 1987).

An Inventory of Relations between Local Surface Regions

For a local property map to be useful as a perceptual representation of 3D surface structure, it would have to be accompanied by appropriate mechanisms for comparing the properties in different locations. Consider a possible stimulus surface on which two small local regions (p1 and p2) have been highlighted. Suppose this is presented to a human observer who is asked to judge how the properties of those regions differ from one another. The mechanisms required for performing this task are critically dependent on how the question is posed, since there are several different types of relations that need to be considered.

Metrical Relations -- The most complex type of relation between a pair of surface regions is one that involves a single distance measure along several simultaneous component dimensions. Suppose, for example, that the position of each point is represented using a Cartesian coordinate system (x, y, z) where the principal axes are aligned horizontally, vertically and in depth. In order to determine the total distance between a pair of points using such a representation, it would first be necessary to calculate the difference between them along each individual dimension, and to then employ a *metric* for combining these measures into a single overall distance. The metric of Euclidean space is defined by the Pythagorean theorem, but there are many other possibilities that could be used in principle by our perceptual systems.

Interval Relations -- A somewhat simpler type of relation is one that involves a distance measure along a single dimension of the underlying representation. To assess the perception of interval relations, an observer might be asked to estimate the distance in depth between two local surface regions or to judge whether the difference in the slant component of their local orientations is greater than 30 degrees. If depth and slant are primitive local properties of our perceptual representations, as is sometimes assumed, then the computation of distance along these component dimensions need not require the use of a metric for defining distance in a multi-dimensional space.

Ordinal Relations -- Other possible relations between different surface regions are ordinal in nature, without necessarily requiring that the magnitude of their differences be computed. Consider, for example, the perceptual effects of occlusion in monocular pictorial displays. If an image of a tree is occluded by an image of a house, then the house must be closer in depth, but the occurrence of occlusion provides no information whatsoever about the magnitude of their separation.

Nominal Relations -- There is some evidence to suggest that the most primitive type of relation between a pair of surface regions is whether they are members of the same category. If two dots were painted on a persons face, for example, we might notice whether or not they are both located on the nose, even if we were uncertain about their relative depths, orientations or curvatures. Many theorists believe that the decomposition of a surface into parts is a fundamental property of our perceptual representations (e.g., see Hoffman & Richards, 1984; Richards, Koenderink & Hoffman, 1987), but there is little empirical evidence to reveal precisely how these parts might be defined for arbitrarily curved surfaces, such as the one shown in Figure 1. One important nominal category that is well defined, however, is the set of corresponding positions for individual surface points that are viewed from different perspectives. Adopting another example from faces, we can easily identify the tip of the nose or the cleft of the chin regardless of the vantage point from which they are viewed, though it remains to be determined the extent to which observers are sensitive to this identity relation for more generic surface points.

Observer Sensitivity to Perceived Local Structure

In a recent series of experiments, Todd and Norman (1995) and Norman and Todd (1996) have begun to investigate the ability of observers to discriminate various types of relationships between the local properties at different probe points on a smoothly curved surface. The stimuli employed in these studies were generated by adding a set of sinusoidally corrugated surfaces to a sphere in randomly selected orientations. These objects were covered with a wireframe mesh, composed of several thousand triangular polygons, and they were shaded and textured using an SGI graphics system such that all areas of the surface in 3D were statistically isotropic (e.g., see Figure 1). The surfaces were presented to observers stereoscopically using a Crystal Eyes electronic shutter system (see Todd & Norman, 1995, for a more complete description of the stimulus generation procedure).

On each trial, a randomly generated curved surface was presented with two test regions highlighted by small colored dots. The observer's task was to judge whether the difference in depth or orientation between the two designated regions was greater or less than an implicit standard, which they were able to learn from immediate response feedback over a repeated sequence of trials. Previous research has shown that discrimination thresholds measured with this procedure are equivalent to those obtained using a two interval forced choice paradigm where the standard is presented explicitly on every trial. Each block of trials contained eight different test intervals for a fixed standard presented 50 times each in a random order, and was preceded by a series of 25 practice trials. From the results obtained over two separate blocks for each standard, the best fitting cumulative normal distribution was calculated using probit analysis. The threshold was defined as half the distance between the 25% and 75% points on the resulting psychometric function.

In one experiment performed by Norman and Todd (1996), discrimination thresholds for depth and orientation intervals were measured for three observers. Three different standards were selected for each condition, representing the first, second and third quartiles from the distribution of depth and orientation intervals over all possible point pairs on the depicted objects. The standard depth intervals obtained by this procedure were 1.35, 2.7 or 4.05 cm., and the standard orientation intervals were 42.5, 70.9 or 99.2 degrees. Eight possible test intervals were chosen for each standard based on pilot investigations to span an appropriately wide range of difficulty in the required judgments.

The thresholds obtained in each condition were converted to Weber fractions by dividing the discrimination threshold by the magnitude of the standard. The results are shown in Figure 2. Note in the figure that observers were surprisingly insensitive to the magnitudes of the depicted depth intervals (i.e., their Weber fractions ranged from 0.16 to 0.44), but that performance was significantly improved for judgments of orientation intervals. A similar result has also been reported by Koenderink, van Doorn and Kappers (1996).

Suppose hypothetically that observers' judgments of local orientation are obtained by differentiating a more primitive representation of depth. Because some amount of error would likely be introduced by the process of differentiation, we would expect in that case that performance would be higher for judgments of depth than for judgments of orientation, which is clearly inconsistent with the available psychophysical evidence. Suppose, however, that judgments of surface depth are obtained by integrating over a more primitive representation of local orientation. In order to perform this type of computation, it would be necessary to integrate along a path on the surface that connects the two probe points, and the error associated with this operation would be likely to increase as the distance between the probe points becomes greater and greater. Norman and Todd (1996) performed a follow-up experiment to test this prediction.

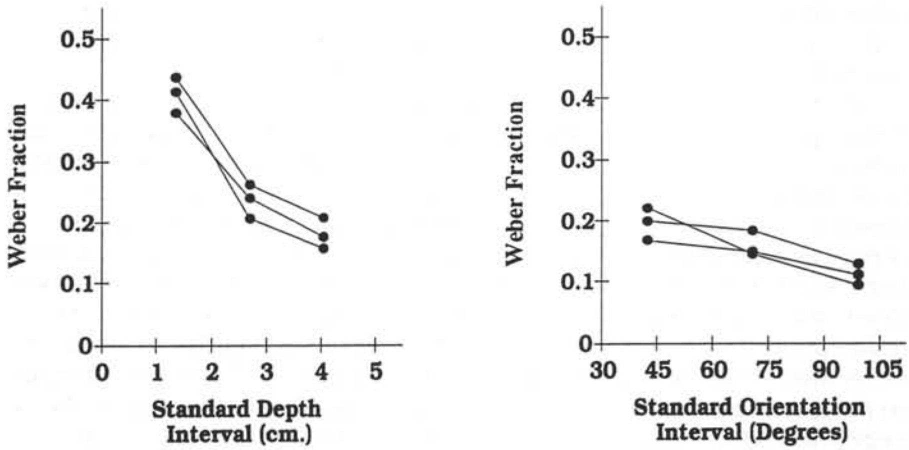

Figure 2 -- The Weber fractions of three observers for discrimination of depth and orientation intervals.

The procedure was identical to the one described above with two exceptions: First, a single standard was employed in each condition -- 2.7 cm. for the depth interval discriminations and 70.9 degrees for the orientation interval discriminations. Second, we also varied the spatial separation in the image plane between the two probe dots. In the *Near* condition, the selection of probe dots was constrained so that the distance between them in the image was no greater than 4.0 cm., while in the *Far* condition they were constrained so that the distance between them would be no less than 4.0 cm.

The results for three observers are shown in Figure 3. Note in the figure that there were large effects of probe point separation for the depth interval discriminations, but not for judgments of orientation intervals. This finding is consistent with the hypothesis that depth intervals are computed from a more primitive representation of surface orientation. Norman and Todd (1996) performed an additional experiment, in which the probe dots are presented in empty space without being attached to a visible surface. The effect of spatial separation in that case was greatly attenuated. It would appear from this result that observers can compute depth intervals directly between points in empty space, but not between points on a smoothly curved surface.

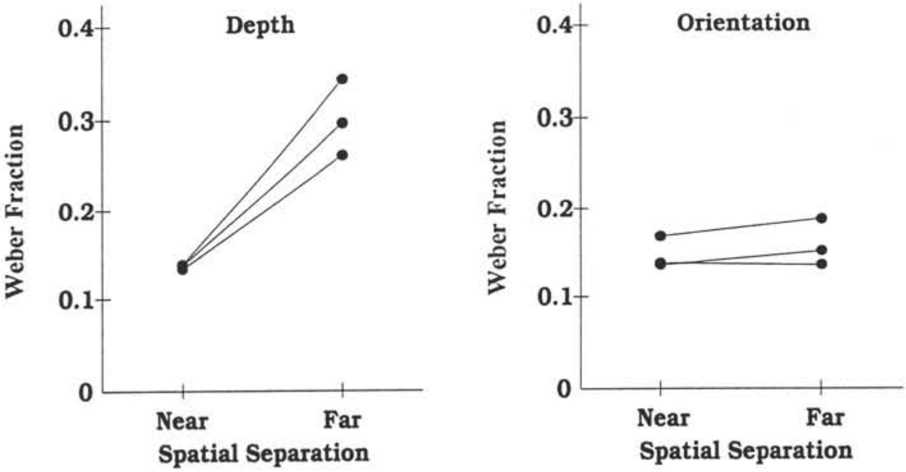

Figure 3 -- The Weber fractions of three observers for discrimination of depth and orientation intervals as a function of the spatial separation of the probe dots.

Could local orientation be the primary basis of our perceptual representations of smoothly curved surfaces, from which all other aspects of 3D structure must be derived? A recent series of experiments by Johnston and Passmore (1994) provide compelling evidence that this is not the case. They measured observers' discrimination thresholds for both orientation and curvature on smoothly curved surfaces defined by stereo, shading and texture in varying combinations. As the direction of illumination for shaded displays was slanted closer and closer to the observers line of sight, performance was facilitated for judgments of surface orientation, yet that same manipulation impaired performance for judgments of surface curvature. Similarly, when texture was added to the displays, observers became more sensitive to differences in surface orientation, and less sensitive to differences in surface curvature. If perceived curvature were derived from a more fundamental representation of local orientation -- or vice versa -- it would not be possible for a given stimulus manipulation to have opposite effects on each type of judgment.

Constancy of Perceived Local Structure

Another important aspect of perceptual performance that needs to be considered in evaluating local property maps as potential representations of 3D form is their stability under changing viewing conditions. Consider, for example, a typical solid object encountered in the environment, such as a rock or a potato. An object in the environment can be observed under a wide variety of different conditions: It can be moved from one position to another; it can be rotated to different orientations; it can be painted or papered to alter the manner that its surface reflects light; it can be subjected to different patterns of illumination; and it can be observed either monocularly or stereoscopically. It is important to keep in mind that none of these manipulations would have any effect at all on an object's shape as defined objectively in 3D space, but how might they affect the subjective appearance of shape or the structure of an observer's perceptual representations?

There is a considerable body of evidence to suggest that at least some of these changes can produce systematic distortions in an observer's perception of 3D structure, which are sometimes referred to as failures of object constancy. For example, there are numerous reports in the literature that when the viewing distance of an object is increased, under full cue conditions, there is a systematic expansion of its perceived height and width in the frontoparallel plane and a systematic compression of its perceived extent in depth (e.g., see Baird and Biersdorf, 1967; Loomis, Da Silva, Fujita, and Fukusima, 1992; Tittle, Todd, Norman & Perotti, 1995; Norman, Todd, Perotti & Tittle, 1996). A good example of this latter effect has recently been reported by Todd and Norman (1996). They asked observers to adjust the shape of a stereoscopically presented pyramid so that the distance from its base to its tip in depth appeared to be the same as the width of its base in the fronto parallel plane. On some trials, the pyramid was presented as a wireframe outline, while on others it was shown with a simulated marble texture on each of its visible faces. The displays were also viewed from two different viewing distances of 57 and 172 cm, which were varied across blocks.

Figure 4 shows the perceived depth to width ratios in the different conditions averaged over six observers. Note in the figure that the effects of viewing distance were consistent with those obtained in previous investigations. That is to say, the pyramid depths were systematically overestimated at the near distance and systematically underestimated at the far distance. In addition, there was also a significant effect of the different modes of depiction, such that the textured pyramids appeared to have more depth than did the wireframe pyramids.

Although the methodology employed in this study is sufficient to demonstrate a failure in shape constancy due to changes in viewing distance or the pattern of reflectance, it is much too crude to pinpoint a specific pattern of distortion in the perceptual representation of 3D form. Indeed, that is also the case for most other experiments on shape constancy, in which observers' judgments of an entire object have typically been limited to only one or two parameters, such as its height, width or depth. In order to provide a reasonably precise measure of perceived 3D shape that is applicable to arbitrary surfaces, it is obviously necessary to provide observers with a much larger number of degrees of freedom in making their judgments.

A particularly clever method for satisfying this criterion was developed by Gregory (1966). He created an apparatus called "Pandora's box" with which a stereoscopically viewed probe can be superimposed over a monocular pictorial display of a 3D scene. At any given location in the monocular image, an observer adjusts the depth of the probe until it appears to rest on the surface of the depicted object. This can be repeated at many different locations in order to obtain a reasonably precise sample of the overall pattern of perceived surface undulations. The same basic procedure can also be used to estimate the perceived 3D structure of smoothly shaded surfaces that are viewed stereoscopically (e.g., see Bulthoff & Mallot, 1987; Koenderink, Kappers, Todd, Norman & Phillips, 1996), though it cannot be used with stereograms of textured surfaces, since the observers in that case could perform the task trivially by adjusting the probe to match the disparities of nearby texture elements.

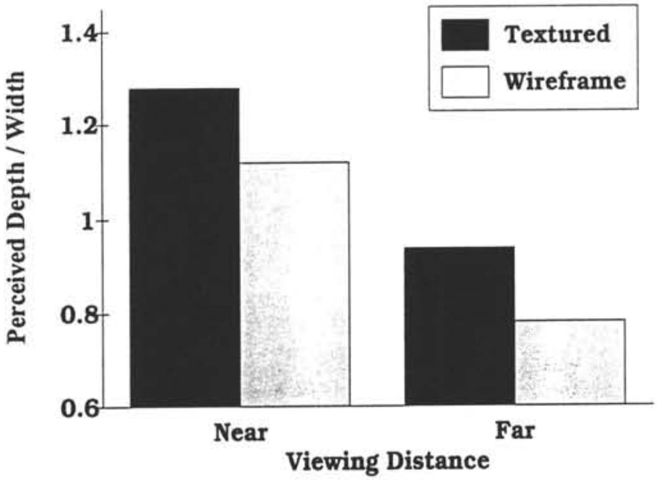

Figure 4 -- Perceived depth to width ratios of textured and wire frame pyramids at two different viewing distances. A value of 1.0 would be perfect performance.

An alternative approach to avoid this limitation involves judgments of local orientation at many different probe points on an object's surface (e.g., see Koenderink, van Doorn & Kappers, 1992, 1994, 1995; Koenderink & van Doorn, 1995; Koenderink, Kappers, Todd, Norman, & Phillips, 1995; Mingolla & Todd, 1986; Norman, Todd & Phillips, 1995; Todd, Koenderink, van Doorn & Kappers, 1995). This can be accomplished in a variety of ways, but the most common technique is for observers to a adjust the 3D orientation of a circular disk, called a gauge figure, until it appears to rest in the tangent plane at some designated location. For stereoscopic displays, the gauge figure is presented monocularly so that the adjustment cannot be achieved by matching the disparities of nearby texture elements. Although the specific depth of the gauge figure is mathematically ambiguous in that case, most observers report that it appears firmly attached to the surface, and that they have a high degree of confidence in their adjustments. A similar technique can also be used with moving displays (Koenderink, Kappers, Todd, Norman & Phillips, 1996). However, to prevent matches based on the relative motions of nearby texture elements, the task must be modified somewhat so that observers adjust the shape of an ellipse in the tangent plane until appears to be a circle (Norman, Todd & Phillips, 1995). This latter variation has also been used for the direct viewing of real objects by adjusting the shape of an ellipse that is projected on a surface with a laser beam (Koenderink, van Doorn & Kappers,1995).

Koenderink, van Doorn & Kappers (1992, 1994, 1995) have recently developed a powerful procedure for computing the pictorial relief of the best-fitting surface whose normals are most consistent with an observer's judgments of local orientation over an appropriately large sample of probe points. This also provides a simultaneous confirmation that the overall set of judgments has a consistent interpretation as a smoothly curved surface, which is a nontrivial result. The interpretation is consistent if the least squares error is no larger than the standard deviation over multiple judgments for individual probe points, which is typically around 15% or 20% for the slant component and about half that for tilt.

During the past several years, Koenderink and his collaborators have compared the precision of this technique with other possible methods of probing the perceived structure of a depicted surface. For example, in one recent study by Koenderink, Kappers, Todd, Norman & Phillips (1996) observers judged the 3D structure of a moving shaded stereoscopic surface using a local orientation probe and a local depth probe (i.e., the "Pandora's box" technique). The patterns of pictorial relief obtained using both methods were highly correlated ($r = .95$), which strongly suggests that they are both valid measures of a single underlying data structure. It is also interesting to note, however, that the orientation probe is slightly more reliable. That is to say, for a given set of probe points, the standard errors are slightly smaller for the orientation probes than they are for the depth probes. Similar findings have also been obtained by Koenderink, van Doorn and Kappers (1996) in comparing the results for local orientation judgments on photographs of a human torso, with an alternative method of surface reconstruction from judgments of local depth order relations between all pairs of neighboring probe points. When considered together with the discrimination studies of Norman and Todd (1996) described earlier, these findings provide strong evidence that local surface orientation is a more salient aspect of 3D structure than is local surface depth.

Other experiments have been performed using this technique to evaluate the constancy of perceived shape under a variety of changing viewing conditions. For example, in a recent study by Todd, Koenderink, van Doorn and Kappers (1996) observers performed the gauge figure adjustment task with monocularly and stereoscopically viewed photographs of a male and a female mannequin. The results revealed that monocular displays produced less perceived relief than the stereoscopic displays. There were also systematic distortions produced by changing the direction of illumination. Although there were some variations among the different observers and conditions, there was significantly more perceived relief when the depicted torsos were illuminated obliquely from the side than when the illumination was aligned with the observer's line of sight.

In a closely related experiment, Koenderink, van Doorn and Christou (1995) compared performance on the gauge figure adjustment task for a contour drawing of a human torso with monocular photographs of the same object taken with varying directions of oblique illumination. The results revealed that observers' perceptions of these stimuli were remarkably similar. There was, however, a small but reliable pattern of distortion caused by changing the direction of illumination, such that the perceived relief tended to be sheared slightly toward the light source.

Another important factor that can influence the perceived shape of an object is its pattern of surface reflectance. To investigate this phenomenon, Todd, Norman, Koenderink and Kappers (1996) examined observers local orientation judgments for: 1) smoothly shaded matte surfaces with a Lambertian reflectance function that scatters light equally in all directions; 2) smoothly shaded shiny surfaces with specular highlights; and 3) textured surfaces resembling granite with Lambertian shading . The stimulus objects were generated at random using the same procedure as described earlier for the discrimination experiments of Norman and Todd (1996) – see Figure 1. Each object was viewed stereoscopically, and observers were required to adjust a monocularly presented circular gauge figure at numerous probe points arranged over its surface.

Although the 3D structures of the depicted objects were identical in all of the different reflectance conditions, there were significant variations among the reconstructed surfaces computed from the observers' adjustments. Figure 5 shows the reconstructed depths of a typical observer plotted against the actual surface depth at each probe point. Note in the figure that the linear correlation is quite high in all three conditions, but that the regression lines vary somewhat in their slopes. Over all of the different objects and observers the average correlation squared for the textured, shiny and matte conditions was .91, .85 and .81, respectively, and the average slopes of their regression lines were .70, .66 and .56. In other words, the reconstructed surfaces all had significantly less relief than did the actual depicted objects. Textured surfaces were judged more accurately than those that were smoothly shaded, and the shiny surfaces produced more perceived relief than the matte surfaces. This last result is particularly interesting given that most computational analyses of shape from shading are based on an assumption that the surface reflectance function is Lambertian. It would appear that this is not the case, however, for actual human observers.

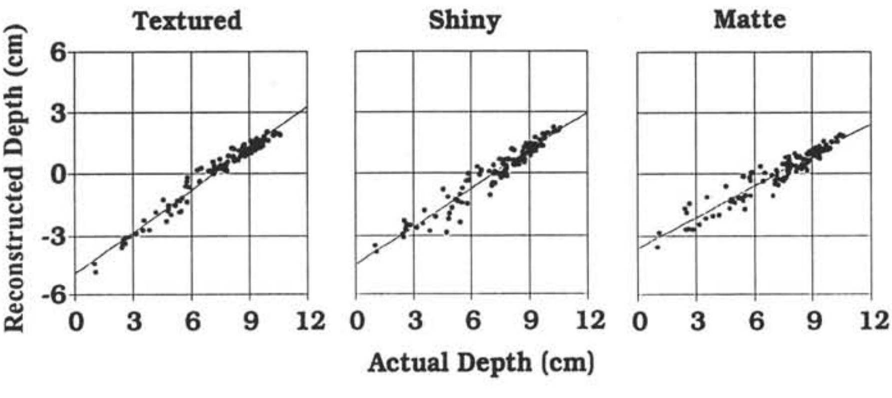

Figure 5 -- The reconstructed depths of a typical observer for identical objects depicted with three different types of surface reflectance.

Conclusions

The research described in the present article has been designed to investigate the ability of human observers to judge various aspects of local 3D structure on smoothly curved surfaces defined by shading, texture, motion, and binocular disparity. In one set of experiments observers were required to discriminate interval relations of depth and orientation. On each trial, a randomly generated curved surface was presented with two test regions highlighted by small colored dots. The observer's task was to judge whether the difference in depth or orientation between the two designated regions was greater or less than a predefined standard. The results revealed that Weber fractions for discriminating depth intervals were roughly twice as large as those obtained for discriminating differences in local orientation. Moreover, observers' sensitivity to the depth difference between two probe dots increased dramatically with their spatial separation in the image plane, whereas similar manipulations had no effect on judgments of surface orientation differences. These findings are consistent with the hypothesis that judgments of depth intervals on smoothly curved surfaces may be performed by integrating over a more primitive representation of local orientation.

In a second group of experiments, observers performed adjustment tasks to estimate the local depth or orientation at individual probe points on an object's surface. The results confirm the findings of our discrimination studies that judgments of local orientation are significantly more reliable than are judgments of local depth. They also reveal that observers' perceptions of local metric structure exhibit large violations of constancy when viewing conditions are varied. In general, these distortions of perceived shape are approximately affine in nature, such that most violations of constancy involve changes in the perceived relief of an object in depth. The evidence suggests that there are a wide variety of stimulus factors that can influence the magnitude of perceived relief. Objects at near distances have more apparent relief than those at far distances; objects illuminated obliquely from the side are perceived to have greater depth than those illuminated along the line of sight; textured objects have more perceived relief than those that are smoothly shaded; shiny surfaces have more apparent depth than matte surfaces; and objects viewed stereoscopically appear to have more relief than those viewed monocularly.

Although observers typically do not notice such effects in natural vision, they can be quite compelling if one pays careful attention. A particularly salient example can be experienced while driving on a divided highway on which dashed lines have been painted to divide the individual lanes. If one looks out at a distance of several meters, the dashed line segments will appear relatively short, but as they become closer and closer to the point of observation, their perceived lengths can increase dramatically by a factor of three or four. This effect is generally not noticed however in the absence of attention, such the visual ground surface appears perfectly rigid and stable.

Given that there is shape constancy in our conscious experience of environmental structure, but not in our judgments of local metrical properties such as depth and orientation, it seems reasonable to conclude that our primary perceptual representation of 3D structure cannot be a local property map of depths or orientations, as is typically assumed in most computational models. An alternative hypothesis suggested by Todd and Reichel (1989) is that visual knowledge may exist at multiple levels of description and that the most relevant form of 3D representation for any given task depends on the particular judgment an observer is asked to perform. There is a growing body of evidence to indicate that performance is most difficult for tasks that require an accurate knowledge of metrical relations among lengths and angles in different positions and orientations. Many of the tasks that we perform most easily, such as object recognition, seem to involve a more qualitative description of 3D structure involving ordinal and topological relations among categorically distinct parts. Although there have been several theoretical analyses proposed in the literature involving part based representations (e.g., see Biederman, 1987; Hoffman & Richards, 1984; Richards, Koenderink & Hoffman, 1987), there has been relatively little empirical research on how such analyses might be applied to randomly structured smoothly curved surfaces like one shown in Figure 1. The extent to which these approaches are compatible with human perception is an important issue that will have to be resolved by future investigations.

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The effect of starting position of the hand on accuracy of pointing

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Abstract

We examined whether performance in manual pointing depends on the starting position of the hand. The hand was visible at the two starting positions but not during the movement. Variable errors in distance were substantially smaller when the pointing movement started from the side than when it started in front of the subject.

Introduction

Pointing at targets in three-dimensional space requires visual information about the position of the target and about the position of the hand. Visual estimates of ego-centric distance show systematic errors (Wagner, 1985). These errors are also evident in manual pointing (Soechting and Flanders, 1989). Vision of the hand during the last stage of the pointing movement allows feedback on the hand's position to be used for positional corrections. Without vision of the hand, the final performance reflects the errors in the initial estimate of distance and direction (i.e. in the estimates of target position at the time of movement onset) combined with errors in assessing the position and movement of the hand. The initial direction of slow goal-directed hand movements shows systematic deviations, similar to those found in an equivalent perceptual task (De Graaf, Sittig & Denier van der Gon, 1991). De Graaf et al. (1991) measured systematic errors in initial movement direction, whereas in the present experiment we consider the variable errors in distance.

The main question in this study is whether we can ascribe pointing errors to specific visual or motor origins? Because it is difficult to split the final pointing errors by visual and motor origin when the starting position of the hand more or less coincides with the position of the eye (the viewpoint), we use two clearly different starting positions. We examine whether pointing errors are different when the hand starts at a clearly different position than the position of the eye.

Methods

We asked 4 subjects to point at 9 different targets, 50 times each. The subjects were sitting in front of a mirror "box" (see figure 1) with their head in a chin rest. In the middle of the box there was a mirror in which the subjects could see the targets that were on the top surface of the box. The 9 targets appeared to lie at the bottom of the box. The box was carefully aligned so that its bottom surface coincided exactly with the mirror image of the top surface. The targets were pseudo randomly distributed and of equal size. The subjects moved their hand below the mirror to set a point on a sheet of grid paper that was attached to the bottom. They could not see their hand except at the starting positions. There were two possible starting positions of the hand: one from the front and one from the side, as indicated in the left part of figure 1. The subjects' task was to point at the target as accurately as possible by setting a black dot on the grid paper with a felt-tipped pen. No time limit was imposed on their settings: subjects could make their settings in a way they felt most comfortable (typically one setting about every 4 seconds). Each target had a unique number and a sequence of random target numbers was read aloud by the experimenter. No feedback was given at any time during the experiment.

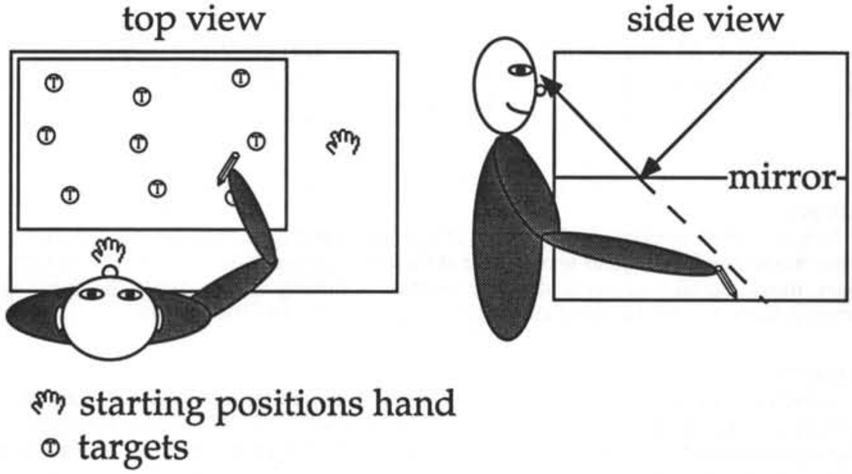

Figure 1 Experimental setup

For each target, the standard deviation in distance was determined relative to two reference positions: relative to eye position (visual error) and relative to the starting position of the hand (manual error). Visual and manual errors can be expected to be more or less the same when the hand starts in front. If pointing errors are mainly caused by visual misjudgements of distance, there should be little change in the visual error when the starting position of the hand is changed from front to side. If pointing errors are mainly caused by misjudgements of movement amplitude, the manual error should not change very much when the starting position of the hand is changed from front to side.

Results and conclusions

Figure 2 shows the standard deviations in distance for each subject and for the two starting positions of the hand. The left part shows the standard deviations defined with respect to the point of view (visual). The right part shows the standard deviations defined with respect to the starting positions of the hand (manual).

The standard deviation in visual distance was always smaller when the hand started from the side, showing that the errors cannot only be due to visual misjudgements. The standard deviation in manual distance was also smaller when the hand started from the side, showing that the errors also cannot only be due to misjudgements of movement amplitude. Thus, it is not clear whether the smaller errors are caused by improvements in visual or motor judgements of distance. Both kind of judgements seem to contribute to the accuracy in manual pointing, which is in line with the conclusion of De Graaf et al (1991).

We hypothesise that vision of the hand gives the opportunity to calibrate visually perceived distance relative to the hand. As a consequence, pointing errors are larger when the required hand movement contains a large component in the direction of visual distance (i.e. when the hand starts in front) than when this component is small (i.e. when the hand starts from the side).

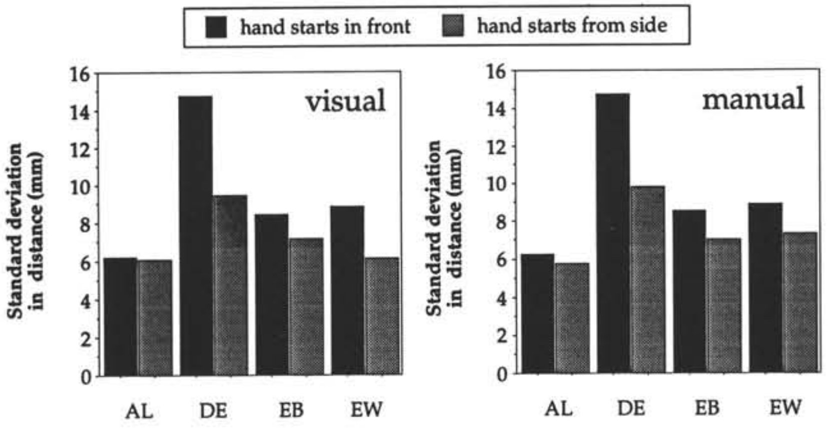

Figure 2 Standard deviation in distance for four subjects

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Visual Control of Position, Velocity, and Deceleration of Neonatal Arm Movements

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Abstract

Arm movements made by newborn babies are usually dismissed as unintentional, purposeless, or reflexive. However, more and more research to date indicates that newborns can move their arms in a purposeful way. The present paper is a more detailed investigation into the nature and possible functional significance of neonatal arm movements. It was found that newborn babies between 10 and 24 days are capable of precisely controlling the position, velocity, and deceleration of their arms so as to keep the hand visible. These findings suggest that newborns can purposely control their arm movements so as to meet external demands and that development of visual control of arm movement is underway soon after birth.

Introduction

As a result of the strong influence of the maturation position, newborn babies are still usually considered reflexive organisms, incapable of making voluntary movements. Maturationists consider the existence and disappearance of reflexes as evidence of nervous system growth and development. As maturation of the cortex and the spinal motor nerve pathways proceeds, the cortical centres supposedly inhibit the primitive reflexes. Cortical maturation and the resulting inhibition of reflexive movements are thought to take up most of the first four months of a baby's life. Until that time, arm movements made by very young babies are simply dismissed as reflexive, involuntary, and purposeless.

Moving a limb or the whole body in a controlled manner requires acting hand-in-hand with gravity and other external forces. Bernstein (1967) was the first to draw attention to the fact that gravity and other non-muscular forces such as the drag of clothing and stiffness of the joints all must be accounted for in controlling the movement of a limb. The consequence is that movements cannot be represented simply as patterns of efference to the muscles nor in any preprogrammed context-insensitive way. Accurate control requires on-line regulation of muscular activation based on perceptual information about the dynamics of the limb movement and the external force field, as well as about the movement of limb relative to objects or surfaces to which it is being guided.

Are neonates capable of such perceptuo-motor control or are their movements to be seen as simply reflexive as is commonly believed? Research on prereaching (Bower et al., 1970; Von Hofsten, 1982) and hand-mouth coordination (Butterworth & Hopkins, 1988) suggests that spontaneous neonatal arm movements are, in fact, aimed and externally directed. Recent work shows that neonates purposely move their hand to the extent that they will couteract external forces applied to their wrists so as to keep the hand in their field of view (Van der Meer et al., 1995). In addition, newborns move their arms more when they can see them (Van der Meer et al., 1996). These results suggest that while looking at their waving arms, newborn babies are developing visual control of movement.

The present paper is a more detailed investigation into the nature and possible functional significance of neonatal arm movements. Are neonates capable of using vision so as to control their arm movements and, if so, how precise is the exhibited control? These are the questions addressed in this paper.

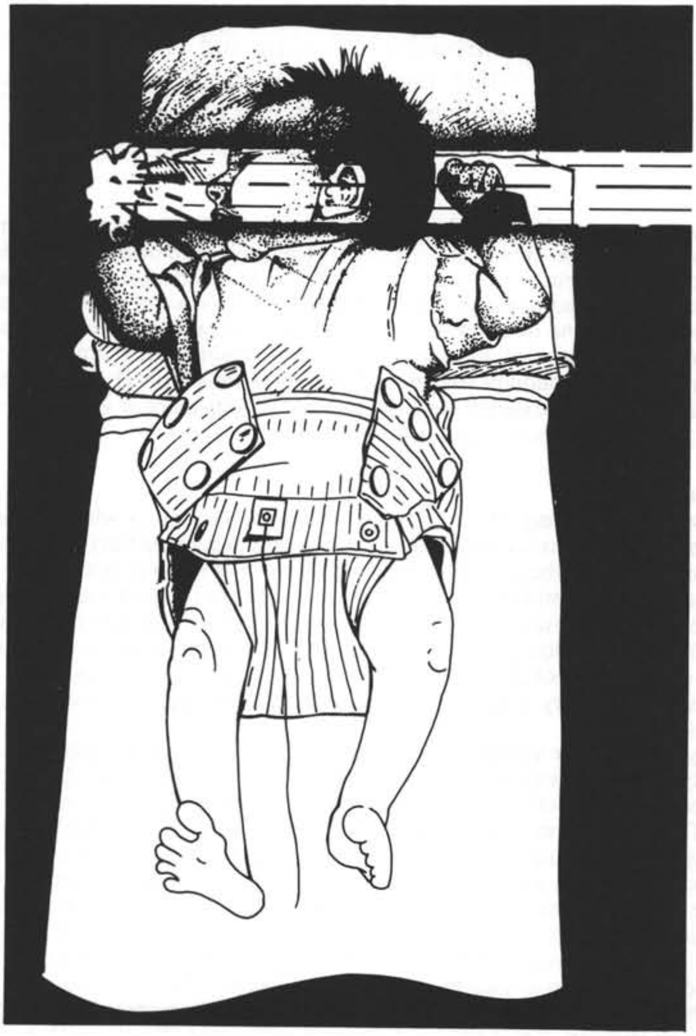

Figure 1. A 21-day-old baby keeping her arm in the 'limelight' - a narrow beam of light (7 cm diameter) in an otherwise dark room. See text for further details.

Method

To test whether newborn babies use vision in controlling their limbs, we measured spontaneous arm-waving movements while newborns lay supine facing to one side (see Fig. 1). Infrared light emitting diodes (LEDs) were fastened onto soft bands around the baby's wrists. The LEDs were viewed by an overhead Selspot camera. The x-axis in the camera's view was lined up perpendicular to the infant's body axis. The Selspot data were recorded on a computer at 62.5 frames per second.

The experiment was carried out under dim lighting conditions with a narrow beam of light (7 cm diameter) shining in one of two positions: high over the baby's nose (as in Fig. 1) or lower down over the baby's chest. The arm the baby was facing and which was only visible when the hand encountered the, otherwise, invisible beam of light, was called the seen hand; the opposite hand the baby was unable to see at all times was called the unseen hand.

Results

POSITION The results show that the babies spent most of the six minutes recording time with their seen hand in the light. As a result, they held the seen hand significantly higher when the light was level with the nose than when it was level with the chest, whereas the wrist position of the unseen hand appeared to be normally distributed with respect to the light position.

SPEED In addition, when comparing the speed of all babies' seen hands when in the actual chest light with the speed in the corresponding area but with the light in the nose position, it was shown that the speed of a seen hand was significantly lower in the light.

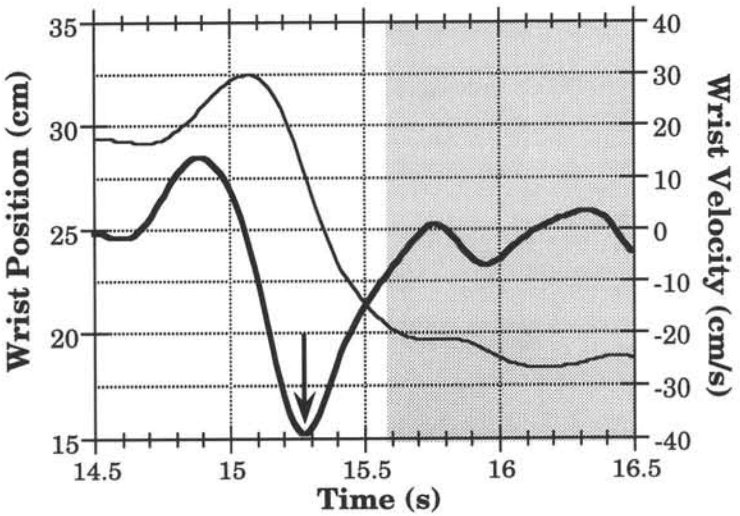

Figure 1. A typical position and velocity record of a newborn baby waving its seen arm with light level with chest. The baby could only see the hand clearly in the shaded area which represents the beam of light. The postition trace (thin line) indicates that baby moves arm 12 cm in the direction of the toes towards the light. The velocity trace (thick line) shows anticipatory deceleration (indicated by arrow) starting 0.3 sec. before the hand enters, and remains in, the shaded visible area. Note that the velocity of the hand in the shaded area is hovering around zero.

DECELERATION Figure 2 shows a typical position and velocity record of a newborn baby waving its arm. For all instances where the baby's hand entered the light and remained there for 2 sec. or longer, the onset of deceleration (point of peak velocity) of the hand was noted with respect to the position of the light. Surprisingly, in more than 75% of all 95 cases, the babies started to decelerate the arm *before* entering the light, showing evidence of anticipation of - rather than reaction to - the light (see Fig. 2). On those occasions where the babies appeared not to anticipate the position of the light, just under 70% occurred within the first 90 sec. after starting the experiment or changing the position of the light. This is clear evidence of both learning and memory in newborn babies. By waving their hand through the light in the early stages of the experiment the babies were learning about and remembering the position of the light. This very quickly allowed them to accurately and prospectively control the deceleration of the arm into the light and remain there, while effectively making the arm clearly visible.

Conclusion

The newborn babies deliberately changed position of the arm, controlled wrist velocity by slowing down the hand, and showed anticipatory deceleration of the hand so as to keep it in the light. This suggests sophisticated control of the hand rather than excited thrashing of the limbs, the way neonatal arm movements have been described in the past. It therefore seems plausible that the spontaneous arm waving of neonates of the kind measured in our experiments is directed and under precise visual control. Neonates can purposely control the position, velocity, and deceleration of their arms so as to keep them clearly visible. Their level of arm control, however, is not yet sufficiently developed that they can reach successfully for toys. Young babies have to do a lot of practising over the first 4 to 5 months, after which they can even catch fast-moving toys successfully (Van der Meer et al., 1994).

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Differentiating Prospective Information for Catching a Big Ball

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Abstract

Interacting effectively with environmental surfaces, objects and other organisms requires prospective control of movement based on predictive perceptual information. A fundamental problem in the coordination and regulation of movement is controlling velocity of approach. A key element in controlling velocity of approach is the perceptual specification of the changing gap between effector and destination and the coupling of this information to coordinate movement elements. In this study the tau theory of perceptual control of approach was proposed as a candidate for providing such information. An experiment involving catching a big ball was used to test the theory. The results were consistent with the rate of change of tau-gap between the ball and the hand being held constant.

Introduction

An optic flow variable of wide application for action is tau ($\tau(x)$), which, in general, is defined as x divided by its rate of change over time (Lee, 1976). The rate of change with respect to time of $\tau(x)$ [= $\dot{\tau}(x)$] is a dimensionless quantity with the interesting property of providing information for controlling deceleration. Analyses of the movement trajectories of a hummingbird aerial docking on a feeder tube, bats slowing down to fly through a narrow aperture, pigeons landing on a perch, people running and slowing down to make facial contact with a surface, and skiers negotiating slalom flags are consistent with deceleration being controlled by keeping $\dot{\tau}(x)$ constant.

This leaves the question open as to how acceleration of movement is controlled. Lee *et al.* (1996) addressed this question in the case of reaching for a small object. Such a movement commonly consists of acceleration from rest followed by deceleration to a destination. From symmetry it was argued that, if deceleration were controlled by keeping $\dot{\tau}(X_{dec})$ constant, where X_{dec} is the gap between the hand and the destination, then acceleration might be controlled by keeping $\dot{\tau}(X_{acc})$ constant, where X_{acc} is the gap between the hand and the starting position of the reach. The results found in the experiment were consistent with this hypothesis.

In the present experiment the general theory of control of velocity of approach using $\tau(x)$ was applied to the perceptuo-motor skill of one-handed catching a big ball. In a continuous catching and throwing task it was investigated how (1) velocity of the arm was prospectively matched to that of the ball so as to (2) decelerate it smoothly towards zero velocity at the end of the catch.

Method

One experienced and one inexperienced catcher took part in the experiment. Each subject performed 26 continuous catching movements with help of an assistant standing approximately 3.5 metres away. The diameter of the ball was 25 cm. The catching movements were viewed by a video camera with its optical axis perpendicular to the subject's (saggital) plane of movement. A high-speed video system (Kodak EktaPro™) recorded the images at 250 frames/second. These recordings were then played back on a large Sony PVM-201CE monitor screen. The X-coordinates of the leading edge of the ball (X_{ball}) and the processus styloideus of the ulna of the subject's forearm (X_{hand}) were digitized (see Figure 1).

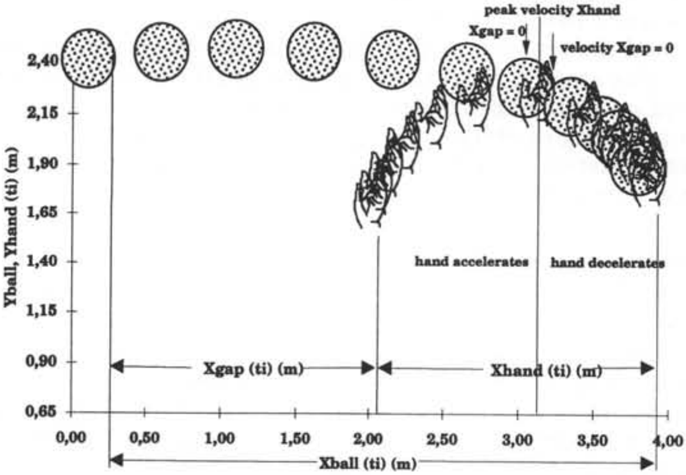

Figure 1. Position coordinates (x,y) of the hand in relationship to the ball during a typical catching action. Only every 10th coordinate (25Hz) is plotted in this graph due to the size of the plot symbols.

Results

Control of hand acceleration: alternative I, $\tau(X_{acc})$.

The region marked "hand accelerates" in Figure 1 indicates the section of the hand movement that was analysed to measure control of hand acceleration. The question was: might hand acceleration of the catch be controlled continuously by keeping $\dot{\tau}(X_{acc})$ constant, where X_{acc} is the gap between the catching arm and the starting position of the catch? To answer the question on each frame $\tau(X_{acc})=(X_{hand}-X_{start})/(\dot{X}_{hand}-\dot{X}_{start})$

was calculated. If control had consisted in $\tau(X_{acc})$ being kept constant during acceleration of the hand then the $\tau(X_{acc})$ against time curves should be linear.

The mean linear regression coefficient of $\tau(X_{acc})$ against time for the experienced catcher was high (M=0.988; SD=0.011), implying that $\dot{\tau}(X_{acc})$ was held about constant. This value was much lower (M=0.636; SD=0.254) for the inexperienced catcher, implying that this subject might have used an alternative control strategy.

Control of hand acceleration: alternative II, $\tau(X_{gap})$.

Instead of controlling arm acceleration by using prospective information from the gap between the catching arm and the starting position of the catch, acceleration of the arm might be controlled by prospective information from the gap between the catching arm and the approaching ball. Figure 1 shows the region over which X_{gap} is analysed over time to measure gap control. On each frame during that time interval $\tau(X_{gap})=(X_{ball}-X_{hand})/(\dot{X}_{ball}-\dot{X}_{hand})$ was calculated. If control had consisted in $\tau(X_{gap})$ being kept constant during gap closure then the $\tau(X_{gap})$ against time curves should be linear. Figure 2 shows $\tau(X_{gap})$ profiles against time of the gap between ball and hand.

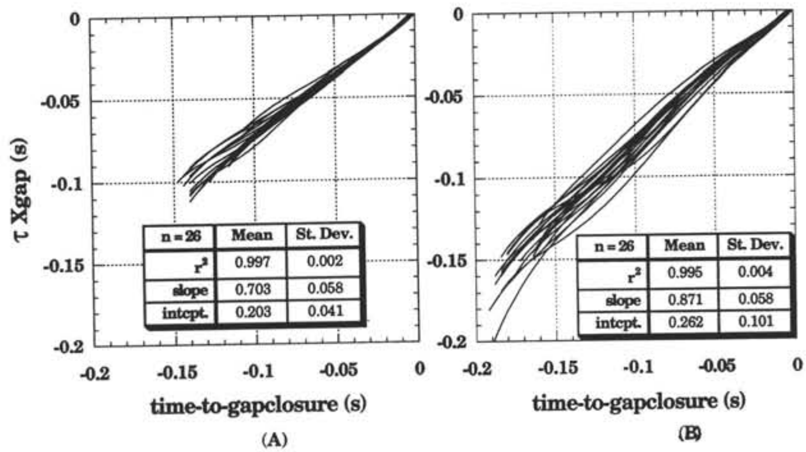

Figure 2. $\tau(X_{gap})$ profiles plotted against time-to-gapclosure for the (a) experienced and (b) inexperienced catcher.

The mean linear regression coefficient of $\tau(X_{gap})$ against time-to-gapclosure for both the experienced (M=0.997; SD=0.002) and the inexperienced (M=0.995; SD=0.004) catcher were very high, implying that $\tau(X_{gap})$ was held constant. Thus, instead of using arm acceleration -as such- as a control variable, acceleration of the arm might be controlled by using information from the environment as well, namely by using information from the gap between the accelerating arm and the approaching ball.

The regression slopes, indicating the rate at which $\tau(X_{gap})$ was held constant, were significantly higher for the inexperienced subject (M=0.871; SD=0.058) than for the experienced subject (M=0.703; SD=0.058). This shows that hand velocity of the inexperienced subject was much higher at the moment of ball-hand contact. This fact resulted in that the inexperienced catcher had a less favourable starting position than the experienced catcher with respect to the actual catch in which *gradual* deceleration of the ball towards zero velocity needed to be established.

Control of hand deceleration: $\tau(X_{dec})$

The region marked "hand decelerates" in Figure 1 indicates the section of the hand movement during ball contact that was analysed to measure control of hand deceleration. The question was: might hand deceleration be controlled continuously by keeping $\dot{\tau}(X_{dec})$ constant, where X_{dec} is the gap between the catching arm and the end position of the catch? To answer the question on each frame $\tau(X_{dec})=(X_{end}-X_{hand})/(\dot{X}_{end}-\dot{X}_{hand})$ was calculated. If control had consisted in $\tau(X_{dec})$ being kept constant during deceleration of the hand then the $\tau(X_{dec})$ against time curves should be linear.

The mean linear regression coefficient of $\tau(X_{dec})$ against time for the experienced catcher was high (M=0.961; SD=0.035), implying that $\dot{\tau}(X_{dec})$ was held about constant. This value was much lower (M=0.614; SD=0.347) for the inexperienced catcher, implying that perceptual information for a constant $\dot{\tau}(X_{dec})$ approach could not be picked up adequately. This was probably due to the subject's inability to regulate arm velocity appropriately at the moment just before ball-hand contact. This resulted in wobbly deceleration profiles and dropping the ball on several occasions.

Conclusion

The results in this experiment were consistent with accelereation and deceleration of hand movement being controlled by keeping $\dot{\tau}(x)$ constant. However, further analyses indicated that control of arm acceleration was better described by keeping $\dot{\tau}(x_{gap})$ constant, where x_{gap} is the gap between the arm and the ball. Thus, instead of using arm acceleration - as such - as a control variable, (acceleration of) the arm was controlled by using relational information between the catcher's hand and the environment.

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How to Probe Different Aspects of Surface Relief

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Abstract

We probe the structure of pictorial (surface) relief with a variety of psychophysical methods. We study the internal consistency for each method, mutual consistency between different methods, as well as the (quite distinct) issue of veridicality. Because these methods yield extensive, quantitative data, we are in a position to (re–)address problems related to the influence of viewing conditions, the influence of various "depth cues" on the relief, and the effects of observer familiarity with the object depicted in the stimulus.

Introduction

When we look at pictures like photographs we experience different modes of perception simultaneously. We perceive a planar sheet, a flat object covered with a pattern of graytones. At the same time, at another level, we perceive a scene in "pictorial space". This is a three–dimensional space. Two dimensions of the pictorial space, namely left–right and top–bottom, tightly correlate with the two dimensions in the picture plane. The third dimension of pictorial space, the "depth dimension" is less tangible.

Opaque objects in a scene obstruct sight into pictorial depth. The surfaces of these objects, so–called "pictorial reliefs", are different from surfaces in our physical environmental space in several respects. For instance, their distance to the observer is ill defined, their depth, that is their "extendedness in pictorial space", is not commensurable with the two dimensions that span frontoparallel planes. These latter dimensions are immediately specified in the visual field of the observer but the depth dimension is an intricate function dependent on picture and observer.

An observer appreciates pictorial depth dependent on his or her competence in reading pictures, prior experience, training, etc. Thus, pictorial depth will vary between observers. Different pictures contain different "signs" from which an observer can extract depth information. Thus, pictorial depth will vary between different pictures. Moreover, pictorial relief is highly dependent on viewing conditions.

We know from their writings that already centuries ago some artists speculated that the three–dimensional extension of pictorial space depends on signs in the scene (Gombrich, 1960). More recently also scientists became interested in these so–called depth cues (Pirenne, 1970). Examples of depth cues are occlusion, perspective, contour information, shading, etc.

At the moment we have some insight in the structure of a number of the classical depth cues. We understand quite a bit of both ecological optics and the structure of the environment. Now we can investigate whether observers indeed exploit their knowledge of depth cues, and to what extent this contributes to pictorial depth.

Traditionally the method of reduction is considered the "pure scientific method". That means, that you try to isolate a depth cue and to study it in its pure state, without interferene with other cues. It appears, maybe not unexpectedly, that you get artificial results which can be very misleading. For instance, if you take out all contour information and present the shading cue alone, pictorial space becomes very ambiguous (Erens *et al.*, 1993). It is not possible to study the influence of shading on pictorial depth in isolation. A picture needs a rich set of cues to make it unambiguous. In daily life we continually see images with a whole gamut of depth cues. Therefore, a better procedure to study a certain cue, is not to isolate it, but to vary it in a rich context of other cues. The parametric variations of the perturbed cue give rise to correlated variations in the observers' response. The correlation reveals the influence of the varied cue.

We use this perturbation method in our psychophysical experiments on form perception and in this paper I give some results.

Methods

Stimuli

In several experiments we used photographs of statues made by professional sculptors. In other experiments we used photographs of mannequins. These schematic torsos are sold for the display of fashion items. They are available in different postures for both genders. Their complicated shapes have intricate contours and shading patterns for many viewing positions and illuminations so that we have ample opportunity to study effects of depth cues.

The photographs of all stimuli were in continuous graytone. The prints were scanned using a Hewlett–Packard Scanjet Plus scanner to 8 bit grayscale pixmaps. The pictures were displayed on a Macintosh 24 bit RGB monitor. We could overlay colored line graphics over the pictures. The subjects could control the overlay graphics by using a trackerball device. In all renditions we checked that the full scale was effectively used (tonal scale editing with Adobe Photoshop). The full scale pictures looked like good quality monochrome postcard–size photographs. In our photographic studio we have effective control over background, lighting directions, shadow and fill in conditions, perspective, pose of the objects, etc.

For preparing our stimuli we could have used convenient computer graphics methods but they typically implement nonphysical processes. We are interested in pictorial realism in a natural environment. Therefore we have chosen for an (elaborate) photographic method.

The region of interest in the picture plane was outlined by hand. This contiguous patch of pictorial surface was then automatically triangulated by a regular triangulation. This triangulation was manually edited to be sure that at all vertices of the triangulation the local pictorial relief was neatly defined. All our triangulations contained about 300 vertices, 700 edges and 450 faces. During the sessions the actual triangulation was never seen by the subjects. Without being aware of it the subjects got the probes always on the vertices and the subsequent data analysis is based on the underlying triangulation.

Subjects and viewing conditions

All experiments were performed by at least three subjects. All subjects had normal visual acuity and good binocular stereo vision. (Some subjects wore their usual correction lenses.) Lights in the room were dimmed. Subjects could distinguish the monitor and they saw that they were looking at a screen on which a picture was shown. They were fully aware of not looking at a real three–dimensional object. Due to an abundance of depth cues in the scene the subjects always reported strong pictorial relief, they never experienced the pictorial object as flat. A head– and chinrest were used to fixate the head of the observer.

Paradigm

To get insight into the geometry of pictorial space you need to gather psychophysical measurements at a large number of locations on your pictorial surfaces. We have developed a general method which has given us this possibility. In principle this method is as follows:

One places a test object (gauge figure or probe) in the scene (or a picture of a gauge figure in a picture of the scene), and asks the observer to judge whether the test figure fits into the scene in some a priori agreed way. The measured response is interpreted in terms of the Euclidean geometry.

For the investigation of different geometrical properties you have to design suitable gauge figures. We have implemented several probing methods to probe various aspects of pictorial relief. In this paper I show by way of some examples two possible lines of application in which one exploits this general probing method.

Firstly, you can use a certain gauge figure to probe the surface of an object in pictorial space. Measurements with such a gauge figure operationally define the perceived pictorial relief. If you prepare a set of pictures of a certain scene in which you vary one depth cue keeping all other cues the same, you can probe the complete set of stimuli with the chosen gauge figure. For all stimuli you use the same operational definition of pictorial relief and you can compare results for the different stimuli and look for the influence of the perturbation of the cue under investigation.

Secondly, you can implement different gauge figures. This gives you two possibilities:

We know that in Euclidean space there exist relations between different geometrical entities. By choosing different probes it is possible to study different geometrical properties of pictorial space. Measurements with each probe operationally define the corresponding geometrical property of the observed pictorial surface. Thus, if you prepare a certain stimulus, you can measure with different probes, independently of each other, different geometrical properties of the same scene. This gives you the possibility to check relations between geometrical entities for perceived pictorial space.

Measurements for each gauge figure gives you another operationalization of a certain aspect of pictorial relief. Thus, it is possible to study different operationalizations of one aspect of pictorial relief by using different, suitably chosen gauge figures. If you prepare a certain stimulus you can measure with different probes, independently of each other, the same aspect of a pictorial surface. In this way you can compare different operationalizations of one entity.

Experiments

Case 1

The observer has to judge a set of stimuli in which we vary one cue keeping all other cues unchanged. With the same probe pictorial relief is measured for each stimulus of the set. By using the probing method in this way we studied the influence of several depth cues. In these studies the gauge figure controlled by the observer is the so–called Tissot indicatrix: an ellipse in the picture plane, overlayed in color (red) over the picture at the location of interest. The task of the observer is to adjust shape and orientation of the ellipse to make it appear as a circle painted on the pictorial surface. The ellipse is interpreted as the projection of a circle: its shape and orientation give you slant and tilt of the local surface element (see Figure 1).

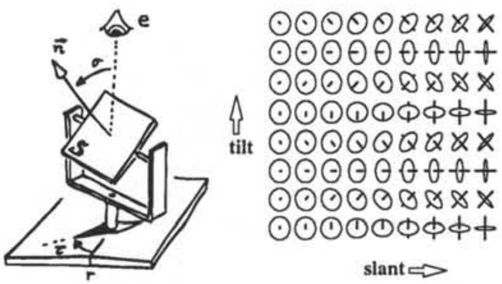


Figure 1: a. Explanation of slant and tilt. The angle between the surface normal and the line of sight defines the slant; it ranges from 0 to 90 degrees. The orientation of the slant defines the tilt. Therefore you need a reference direction in the visual field (for instance left–to–right); it ranges from 0 to 360 degrees. b. Parameter space of gauge figures. Each row has constant tilt, varying slant. Each column has constant slant, varying tilt.

From the slant–tilt settings for all vertices in the triangulation (an example is shown in figure 2) we can compute a reconstruction of pictorial relief and compare the results for different stimulus conditions. (The method and procedure are described in detail in Koenderink *et al.*, 1992.)

Experiment 1

We showed different subjects the same scene under identical viewing conditions and compared their results (see Figure 3).

Subject differences are quite obvious. It seems as if observers put different weights on available cues which results in both patchwise and overall differences in pictorial relief.

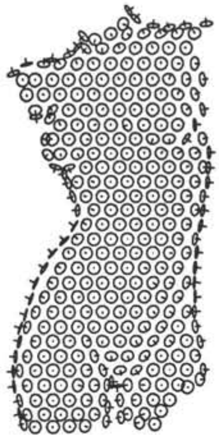


Figure 2: Average gauge figure settings for nine revisits of every vertex. The vertices were visited in random order.

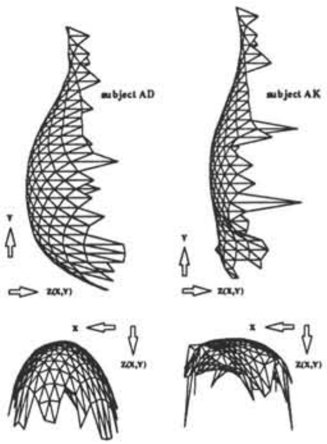


Figure 3: Results for subject AD (left column) and AK (right column). Both subjects judged the same photograph (picture of "The Bird", a sculpture made by Brancusi, at present in the collection of the Philadelphia Museum of Art). In the top row: profile views of the pictorial surface. In the bottom row: top views of the pictorial surface.

Experiment 2

We showed a subject the same scene under different viewing conditions. We compared results for monocular, binocular and synoptical viewing (see Figure 4).

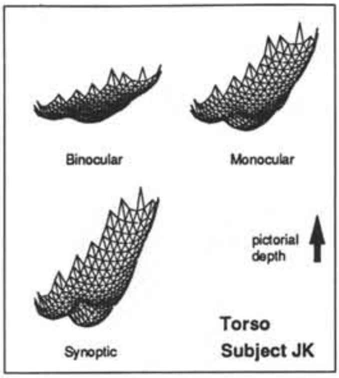


Figure 4: The pictorial surface for subject JK when he judged the same picture (a photograph of an eroded torso) under binocular (a), monocular (b) and synoptical (c) viewing conditions.

The influence of the viewing conditions is striking. A change of viewing conditions for a single picture induces considerable scaling of the depth dimension: in some cases we found even about a factor of two or more difference in global relief. The depth range increases when you change from binocular to monocular viewing. The depth range increases even further when you change from monocular to synoptical viewing. This kind of behaviour was already mentioned in the literature, but until now nobody had quantitatively confirmed this observation (Koenderink *et al.*, 1994).

We not only looked for the influence of viewing conditions if subjects looked at pictures on a screen. We did the same experiments when the subjects looked at a real 3D scene in their physical environment. Results are shown in Figure 5.

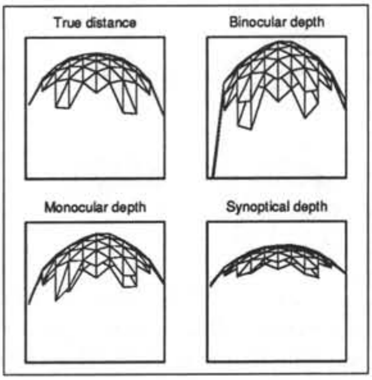


Figure 5: Profile views of the real object (a sphere, painted mat white, diameter 40 cm), and the pictorial surface for subject JK when he judged this real object under binocular (a), monocular (b) and synoptical (c) viewing conditions.

We measured a reversed trend compared to the case of pictorial relief. The depth range is less for the synoptical condition, it is more for the monocular condition, and it is most for the binocular condition. Again, these results are a first quantification of an observation already earlier mentioned in the literature (Koenderink *et al.*, 1995).

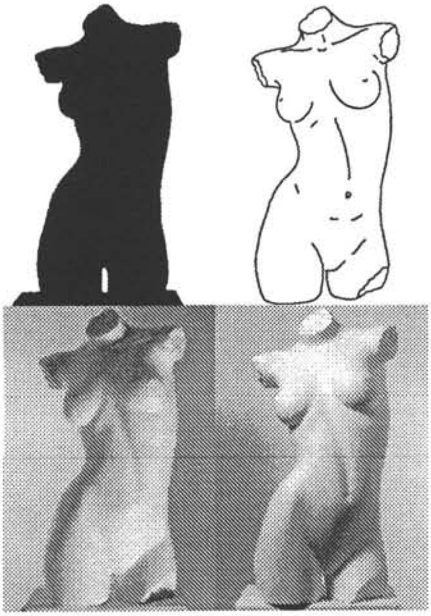


Figure 6: The stimuli. Upperleft: a silhouette rendering. Upperright: a cartoon rendering. Lowerleft: a full grayscale photographic rendering, illumination direction from lowerright. Lowerright: a full grayscale photographic rendering, illumination direction from upperleft.

Experiment 3

We showed a subject the same scene under different rendering conditions. We compared results for the three following cases:

- an object rendered by its silhouette (black on a uniform white ground)
- the same object rendered as a cartoon (black line drawing on a uniform white ground, indicating the visual contour and some key features within this contour)
- the same object rendered in full gray scale (a monochrome photograph of the object, complete with shading, interreflections, etc.)

In all cases the vantage point was the same, thus the perspectives were identical.

With this experiment we studied the impact of the contour information alone on pictorial relief and what is added to it when more information is given. Figure 6 shows the stimuli for the different rendering conditions.

We used two naive subjects. The results of one of them are shown in Figure 7 left. Before we started the experiment this subject was not familiar with the object nor with the pictures of the object. He first judged the silhouette, then the cartoon, and finally the shaded renderings. We also used a non–naive subject. Her results are shown in Figure 7 right. Before we started the experiment she was thoroughly familiar with the object and with the pictures of the object. She first judged the shaded renderings, then cartoon and silhouette.

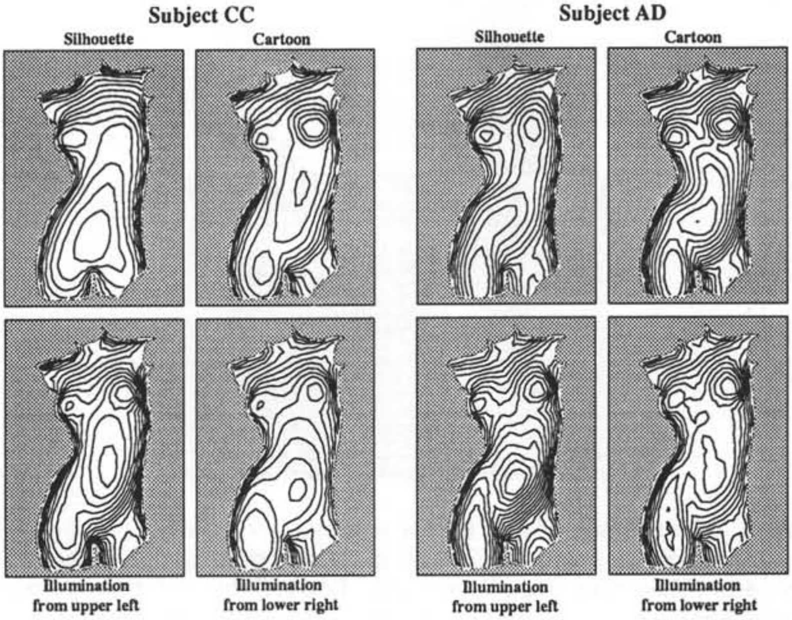


Figure 7: Left: The pictorial reliefs (equidepth maps) of a naive subject (CC) for the different rendering methods. Upperleft: silhouette rendering. Upperright: cartoon rendering. Lowerleft: full grayscale photograph, illumination direction from upperleft (UL). Lowerright: full grayscale photograph, illumination direction from lowerright (LR). Right: The pictorial reliefs (equidepth maps) of a non–naive subject (AD) for the different rendering methods. Upperleft: silhouette rendering. Upperright: cartoon rendering. Lowerleft: full grayscale photograph, illumination direction from upperleft (UL). Lowerright: full grayscale photograph, illumination direction from lowerright(LR) .

It appears that cartoon rendering leads already to a completely developed pictorial relief. A little bit is added by shading cues. The pictorial relief for silhouette rendering is rather impoverished for a naive observer. The interpretation of the pictorial relief for a non–naive observer is reasonably articulate, although inaccurate (Koenderink *et al.*, 1996a).

Experiment 4

We showed a subject the same scene under different lighting conditions. We prepared our stimuli by photographing an object with a number of different light source directions. Camera viewpoint and object posture were equal for all photographs. The subject judged pictorial relief for all stimuli with the same attitude probe (still the elliptical gauge figure) and we could study the influence of the light source direction by comparing the results for the different pictures. In Figure 8 left the contour maps (lines of equal depth) of the pictorial relief for four light source directions are shown.

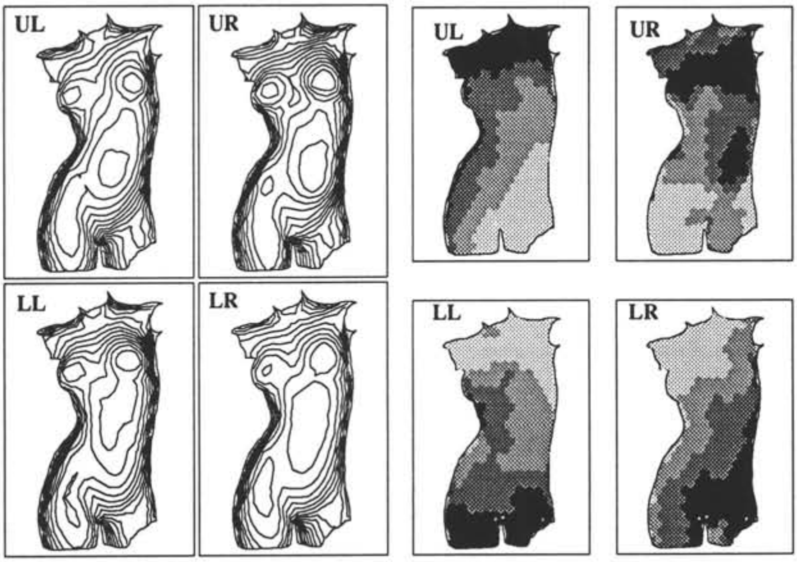


Figure 8: Left: The pictorial reliefs (equidepth maps) for subject JL when he judged the same scene for different light source directions. Upperleft: illumination from upperleft(UL). Upperright: illumination from upperright(UR). Lowerleft: illumination from lowerleft (LL). Lowerright: illumination from lowerright (LR). Right: Depth residuals maps for subject JL for the four illuminance directions. Upperleft: UL. Upperright: UR. Lowerleft: LL. Lowerright: LR.

We calculated the mean pictorial relief from the four conditions. The deviation of the pictorial relief of each condition from this mean pictorial relief is shown in the residuals maps (see Figure 8 right).

We find that shape constancy holds quite well over considerable changes of the illumination direction. However, there are significant differences. It seems that "lighter" tends to be perceived as "nearer" (Koenderink *et al.*, submitted).

Experiment 5

We showed a subject a picture of a certain scene. The same picture was presented under different viewing angles. We compared results for viewing angles between 0 degrees (screen is placed frontoparallel) and 45 degrees (screen is placed oblique under 45 degrees). In Figure 9 the difference is shown between 0 and 45 degrees viewing angle.

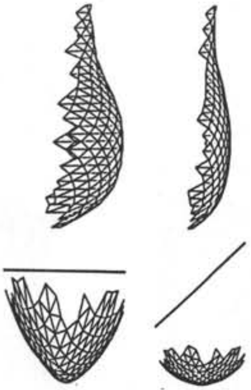


Figure 9: Results for subject AD when she judged the same scene for different viewing angles. Left column: viewing angle 0 degrees. Right column: viewing angle 45 degrees. Top row: profile views of the pictorial surface. Bottom row: top views of the pictorial surface.

In Figure 10 the depth range is plotted for viewing angles between 0 and 45 degrees.

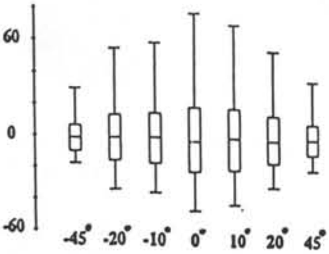


Figure 10: Plot of the depth range for different viewing angles. Subject AD.

The depth range is clearly diminished for oblique viewing: if the obliqueness increases the depth range decreases.

Case 2a

Experiment 6

The observer has to judge the same stimulus with different gauge figures. Each gauge figure probes a different, corresponding, geometrical entity of pictorial space. By this way we studied the relation between zero and first order properties of pictorial relief. Depth (zero order) was measured with a pairwise depth comparison task, depth gradient (slant and tilt, first order) was measured by adjusting form and orientation of an elliptical gauge figure (already introduced above).

For geometrical objects in 3D space it is known that the depth gradient is the derivative of the depth. However, depth and attitude of the pictorial relief as measured in this psychophysical experiment are operationally defined, independently of each other. There is no formal relation between pictorial depth and slant–tilt. With our measurements we could empirically verify a possible relation.

In Figure 11 both tasks are explained. We computed the pictorial reliefs from the attitude settings and from the pairwise depth comparisons. Both reconstructed pictorial surfaces are shown in Figure 12.

Figure 11: Posterized version of the stimulus. The probe for the depth comparison judgements is suggested by the white overlay. In the experiment both dots were filled, one coloured in cyan, the other in magenta. The attitude gauge figure is suggested by the black overlay. In the experiment it was an ellipse with axle in red. In this figure the scale of the overlay figures does not correspond with the actual dimensions.

We find a large difference in precision of the attitude gauge figure settings as compared to the pairwise depth comparisons. Depth from depth comparisons is an order of magnitude less precise than depth from gauge figure settings. Therefore, it seems unlikely that attitudes are derived from a pictorial depth map by differentiation (Koenderink *et al.*, 1996b).

Case 2b
Experiment 7

Again, the observer has to judge the same stimulus with different gauge figures, but now all gauge figures probe the same geometrical property of the pictorial surface. By this way it is possible to compare the results for different operationalizations of the same geometrical property of surface relief.

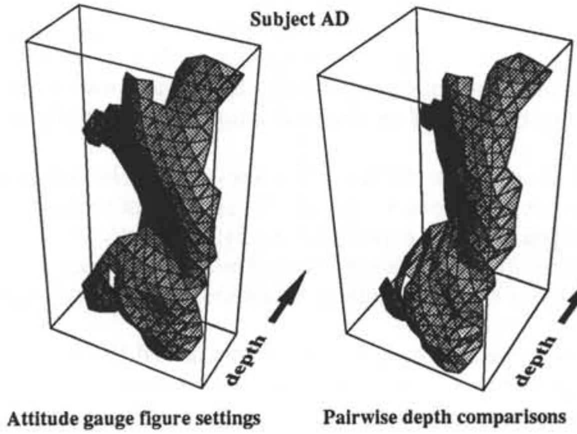


Figure 12: Oblique views of the pictorial surfaces. Left: as calculated from the attitude gauge figure settings. Right: as calculated from the depth comparison settings. Subject AD.

We studied surface attitude (a first order property) with three different probes.

- In the first condition the probe was an arrowhead (in red) superimposed on the picture at the place of interest. The subject controlled the direction of the arrowhead. At all vertices of the triangulation, visited in random order, the subject had to indicate the direction of steepest increase of the depth (the gradient direction) by adjusting the direction of the arrowhead.
- In the second condition the probe was an oriented line piece (in red) superimposed on the picture at the place of interest. The subject controlled the direction of the oriented line piece. At all vertices of the triangulation the subject had now to indicate the direction of equal depth by adjusting the direction of the oriented line piece.
- In the third condition the probe was an ellipse (in red) superimposed on the picture at the place of interest. At all vertices the subject adjusted shape and orientation of this gauge figure so as to appear as a circle painted on the pictorial surface (see above). These settings were converted to slant and tilt (the depth gradient).

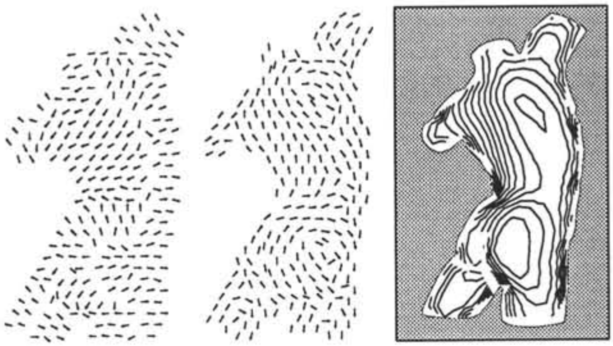
In Figure 13 the different tasks are defined.

Figure 13: Definition of the probes used for different operationalizations of the attitude. Arrowhead: this probe was used to indicate the direction of the gradient. Oriented line piece: this probe was used to indicate the direction of equal depth. Ellipse with axle: this probe was used for the slant–tilt settings by adjusting its form and orientation. In the experiment the probes were overlayed in red. In this figure the scale of the overlay figures does not correspond with the actual dimensions.

Results for each operationalization are given in Figure 14.

The correlation between the different methods is reasonably high. This is illustrated in Figure 15 and Figure 16.

It is possible to compare equidepth direction settings and gradient direction settings by checking their orthogonality. The results for the two independent operationalizations of equidepth directions and gradient directions are plotted together in Figure 17.



a b c

Figure 14: Results for subject AJ. a. Here the plotted arrows are the gradient direction settings averaged over three revisits for every vertex. b. Here the plotted arrows are the equidepth direction settings averaged over three revisits for every vertex. c. Here the equidepth map is plotted as calculated from the slant–tilt settings with the attitude gauge figure.

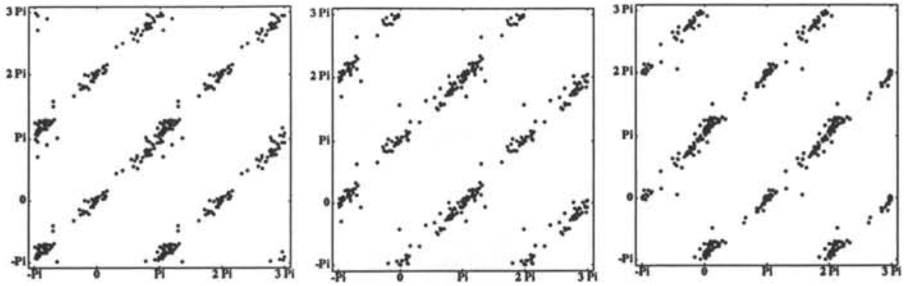


Figure 15: Tilt correlations for the different operationalizations. a. Tilt correlation for attitude gauge figure settings versus gradient direction settings. b. Tilt correlation for attitude gauge figure settings versus equidepth direction settings. c. Tilt correlation for equidepth direction settings versus gradient direction settings.

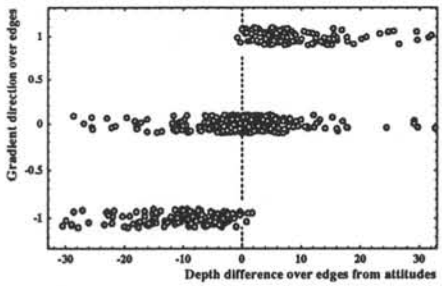


Figure 16: Slant correlation for attitude gauge figure settings versus gradient direction settings. Depth differences along the edges of the triangulation are compared for attitude gauge figure settings (horizontal axis) and gradient direction settings(vertical axis). Assume edge E connects fiducial vertex a with its neighbour vertex b. Then we have used the following conventions. For attitude gauge figure probing: When vertex a is farthest away from the observer the calculated depth difference along edge E is negative, when vertex b is farthest away the depth difference is positive. Zero means no depth difference between the vertices a and b. For gradient direction probing: If the gradient direction setting in vertex a is such that a appeared to be farthest away from the observer, then edge E is assigned a depth difference of -1, and if the gradient direction setting in vertex a is such that b appeared to be farthest away from the observer, then edge E is assigned a depth difference of $+1$. Zero means that vertices a and b are at the same depth. It is clear that the results from both probing methods are highly correlated.

Figure 17: Results for gradient direction settings and equidepth direction settings are plotted together. Per vertex the mutual orthogonality can be checked.

Interestingly, it is clear that equidepth directions and gradient directions as measured with the tasks used in the present experiment, are not mutually orthogonal.

Conclusion

This paper describes a set of experiments in which pictorial relief is probed in several ways at several levels. Probing pictorial surfaces with a gamut of gauge figures appears to be a powerful tool to give some insight in the different aspects of surface perception.

If you want to study an aspect of pictorial relief you have to define a task for the subject. This means that you commit yourself to a certain operationalization of your parameter under investigation. You can expect that your experimental results will be influenced by your operationalizations. Comparing results for different tasks is a useful way to study relations between various aspects of surface perception.

With this in mind it is very well conceivable that probing methods like the ones described in this paper can be useful in practice (for instance in the field of industrial design, virtual reality, computer vision).

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Economics of Tool Recognition

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Abstract

The design of a tool can be perceptively more or less 'suggestive' for its function. The dawn of tool recognition in infancy depends heavily on a highly suggestive design. In a developmental context, we investigated three different perceptual criteria influencing the ease of tool recognition. Those criteria were:

a) The complexity of the relational structure to be anticipated between actor, object and tool.

b) The ambiguity of shape with respect to action.

c) The skill level and/or cultural background of the potential user.

A more or less suggestive parallel will be drawn between our developmental results and modern high-tech tools. Two software tools for designing virtual environments, 'VEGA' and 'SMARTSCENE', will be compared with respect to the three criteria introduced. The examples are meant to provide the basis for a discussion about how tool designers could make use of perception-action research.

Introduction

The application of research on the development of perception and action to tool design is not very obvious. The following examples of such an application should be seen as a demonstration of how a certain problem, like the design of software tools, is structured by a 'foreign' discipline. We would like to discuss if such a description could be useful for designers e.g. in order to direct or systematize the process of designing or to compare different solutions.

In our research we showed how the visual structure of a situation fascilitates or inhibits the recognition of a tool function. The same structural conditions which make it difficult to recognize a tool for a two-years old infant may hold in a way for adults. What changes from infants to adults is the complexity level at which a tool can be recognized.

Developmental Research

The design of a tool can be perceptively more or less 'suggestive' for its function. The dawn of tool recognition in infancy depends heavily on a highly suggestive design. In a developmental context, we investigated three different perceptual criteria influencing the ease of tool recognition. Those criteria were:

- The complexity of the relational structure to be anticipated between actor, object and tool.
- The ambiguity of shape with respect to action.
- Experience/ Tradition

We assume that the same criteria influence performance at all ages but at different complexity levels.

In a developmental study infants were presented with a tool use problem. An object out of reach had to be retrieved by using a hook as a tool. The spatial relationship between target and tool was systematically varied in order to change the complexity of the task in terms of actor-tool-target relationships to be anticipated. Imagine a situation where the target object is presented within the crook part of the hook. In this situation infants as young as 12 months are able to retrieve the target by pulling the hook. The same infant, presented subsequently with a situation were the target lies behind the hook, will not perceive the hook as a tool at all but just try to reach for the target. The first situation is a 'ready for use' one. In the second situation, however, different tool-target relationships have to be anticipated in order to recognize the hook as a tool. Between 18 and 24 months of age infants start to solve the problem in the second situation. The difficulty of recognizing an object as a tool in a situation seems to increase with the number of actor-tool - target relationships to be anticipated.

The hook is ambigue with respect to its potential use in the given task. It can be used as a hook or as a stick. Preference for hook or stick use also changes with the spatial relationship of tool and target given in a situation. In the second situation there is a significantly higher chance for stick use compared to the first situation.

Recognizing an object as a tool depends highly on the experience of the user. Young children have a strong tendency to repeat a way of solving the problem regardless of the economy of an action. If for instance a child solves the first of five trials by using the hook as a stick, the chance for solving the subsequent trials by stick use too is significantly higher compared to a situation where the first trial is solved by hook use. This means that children (as well as designers) tend to structure situations in the same way, using the same invariants that led to success before.

A more or less suggestive parallel will be drawn between our developmental results and modern high-tech tools. The examples are meant to provide the basis for a discussion about how tool designers could make use of perception-action research.

Two software tools for designing virtual realities will be compared with respect to the three criteria introduced. One standing for a big group of software tools that use an mouse-menu interface. We'll call them 'conventional'. The other using an interface exploiting the possibilities to design a virtual reality by acting within virtual space, called 'unconventional'.

Conventional 3-D software

- Number of affordances to be taken in account

For advanced programs in order to perform an action like putting an object into 3-D space, about 20 different nested actions have to be performed. One action doesn't logically lead to the next. The user has to know them. Mistakes become clear after going through a series of other steps that have to be repeated after correction.

The screen is covered with menus which are nested two or even three times. Since the hierarchical structure of functions in the nested menus is not strictly logical, the user has to play a memory game. (An exception is Softimage, known for its user friendliness).

Even professional users need a quite long learning time to become comfortable and agile within such programs.

- Ambiguity of structure

Ambiguity of functions. A lot of icons don't identify their functions in a transparent way.

A lot of results (like moving an object from point A to point B with a certain acceleration) can be reached in different ways using different functions of the respective program. The way chosen may or may not be compatible with other operations the object has to perform. The compatibility is a question of relating functions on the software level. Imagine how difficult it can be to find out that a bug is caused by incompatibility of functions. For a user, who is not a programmer, trial and error is the only way of working.

2D - 3D Ambiguity. Navigating in virtual space with the aid of a mouse causes ambiguity problems. One can get lost very easily e.g. by approaching an object too fast. Finding the way back is hard because the mouse operates in 2-D on a 2-D display representing a 3-D space. Size of the space and scale of the objects can be learned only by trial and error. There are nearly no cues defining the size to depth relationship instantly.

Ambiguity of Scale and Orientation. A centimetre here is not a centimetre there. Importing objects into virtual space from other programs is a case of trial and error concerning scale and orientation.

- Experience/Traditions

The 'Screen-Mouse-Menus' culture in designing software tools. Interface designers start from what is there and recruit their ideas almost only from the interface-world itself. This leads in the present examples to very uneconomic solutions.

Unconventional 3-D software: 'SMART SCENE'

In SMART SCENE a designer steps into virtual space in order to design it. The combination of all ten fingertips and the vertical body axis are used to perform functions in a very intuitive way. Deleting an object e.g. is done by literally grasping it and throwing it over the left shoulder. The ambiguity problems the conventional tools have are all solved by working in a 3-D space. Very view menus are used to let the user chose objects and relevant properties like colour or texture. The menus are smart themselves because they are attached to the objects. This means only those menus which make sense for the object at hand are accessible.

The number of affordances to be taken in account decreases enormously compared to the other tools because actions can be performed in the same way we perform them in the real world. Only a very few actor-tool-target relationships have to be established in order to perform a function on an object. The actions to be performed are highly overlearned. Instead of playing the memory game, the user has to learn a quite small set of gestures, most of them intuitive anyway. By overcoming traditions, the designers of SMART SCENE allow the user to capitalize on his everyday experience with objects.

Conclusion

This analysis is not needed to show that SMART SCENE is a highly effective and economic tool. On a more general level the three criteria introduced could open a discussion about how to help designers to systematically test solutions and improve them on the basis of perception-action couplings. Vice versa, perception-action research could get important impulses from such a validity test. Note that this description is just one preliminary attempt and it is just one example out of a wide variety of approaches which could be applied to tool-design problems.

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Influence of Stimulus Sequence on the Haptic After-effect

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Abstract

The influence of previous history on the haptically judged curvature of a surface is demonstrated. It is found that not only the most recently touched surface contributes to the phenomenal flatness. When two surfaces are touched sequentially, each for 10 s, about 20 % of the final after-effect on a third surface is accounted for by the first surface and about 76 % by the second surface.

Introduction

The subjective correlate of the magnitude of a constant stimulus often tends over time to some base line level. This phenomenon, called adaptation, often co-occurs with an after-effect. We have demonstrated (Vogels et al., 1996) that when subjects touched a concave suface followed by a flat surface they more often judged the latter to be convex than when they began by touching a convex surface. The magnitude of this haptic after-effect increases with the curvature of the preceding surface; after 5 s the after-effect is about 20 % of the preceding curvature. The strength of the after-effect is also enhanced by the duration of contact with the first surface; the build-up can be described by a first-order integrator with a time constant t_b of 2 s. The magnitude of the after-effect decreases with an increasing time interval between the touching of the two surfaces; this decrease can be described by an exponential decay with a time constant t_d of about 40 s.

Because the decay of the after-effect is an order of magnitude slower than the build-up, it is conceivable that the judged curvature of a surface can be influenced not only by the most recently touched surface but also by other preceding surfaces. This hypothesis is tested by measuring the after-effect after two succeeding surfaces have been touched, each for 10 s. A contact duration of 10 s is sufficient to evoke a saturated after-effect and after a delay of 10 s this after-effect has not vanished completely. Suppose that the final after-effect is a summation of the after-effects of the two surfaces, the decay of the first after-effect having been taken into account. If touching a second surface does not influence the decay rate of the after-effect of the first surface ($t_d = 40$ s), both the first and the second surface will affect the final after-effect. The influence of each surface will depend on the curvature of the surfaces, but the relative influence of the second surface will be stronger. If the decay rate of the first after-effect depends on the second surface, the relative influence of the first surface might be different.

Method

Two naive paid subjects participated in the experiment (MV and LV). Both were strongly right-handed, according to the definition of Coren (1993). The stimuli had a spherical upper surface, a flat bottom and a diameter of 20 cm (see figure 1). Stimulus curvature ranged from -4 /m (concave) to +4 /m (convex). Curvature is expressed as reciprocal radius. Subjects placed their right hand on a surface for 10 s. They

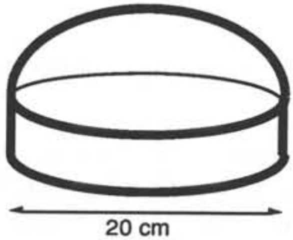

Figure 1: a convex spherically curved stimulus

transferred their hand to a second surface, which they also touched for 10 s. After these two *conditioning* surfaces, subjects touched a *test* surface and decided whether this third surface was convex or concave. No exploratory movements were allowed during the experiment. All surfaces were in the same position with respect to the subject's thorax when they were touched. The conditioning surfaces could have a curvature of -4, 0 or +4 /m. All possible combinations of first and second conditioning curvature were presented to subject MV: -4/-4, -4/0, -4/4, 0/-4, 0/0, 0/4, 4/-4, 4/0, 4/4 /m. Only the combinations for which the first conditioning surface was curved were presented to LV. Each combination was presented together with 7 differently curved test surfaces, each of which was presented 10 times. A psychometric function was fitted to the percentage of convex judgements (see figure 2).

Results

Figure 2 presents an example of a psychometric curve in the case of two flat conditioning surfaces, for subject MV. The shift of the psychometric curve corresponds to the curvature for which convex and concave judgements are equally frequent, and is called *phenomenal flatness*. If the judgements were veridical, the phenomenal flatness would be zero. In figure 2 the surface which is perceived as flat corresponds to a geometrically concave surface of -0.61 /m. We have already shown (Vogels et al., 1996) that subjects usually judge a geometrically concave surface to be flat after touching a flat surface.

The threshold of the psychometric curve did not depend on the conditioning

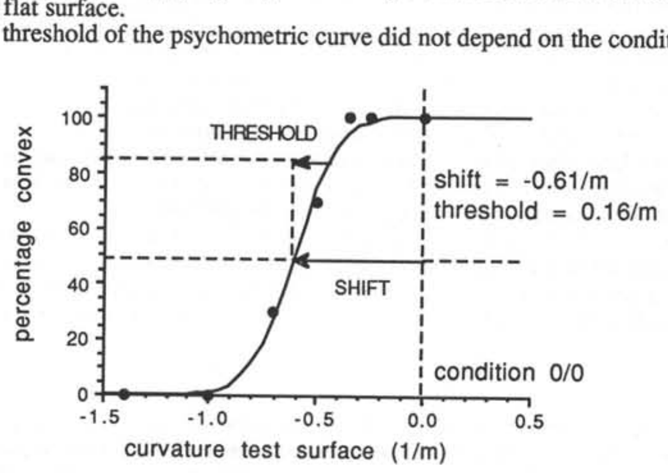

Figure 2: percentage of convex judgements in the 0/0 condition, subject MV

combination. The mean threshold was 0.22 ± 0.04 /m (MV) and 0.20 ± 0.05 /m (LV). The phenomenal flatness, however, did depend on the conditioning combination. This means that each combination of touched surfaces influences the perceived curvature in a different way.

Figure 3 shows the phenomenal flatness for all combinations of conditioning surfaces, for both subjects. The phenomenal flatness is plotted against the second conditioning curvature for fixed first conditioning curvatures. Two combinations for which the curvature of the first conditioning surface is the same are more different than two combinations for which the curvature of the second conditioning surface is the same. This is also clear from figure 4, which shows psychometric curves (without datapoints) in the case of fixed first and fixed second conditioning surfaces. Apparently, the second conditioning surface has a stronger influence on the resulting after-effect. Multiple regression analysis yielded regression coefficients of 0.06 (first surface, R^2 = 9 %) and 0.17 (second surface, R^2 = 86 %) for MV, and 0.04 (first surface, R^2 = 30 %) and 0.07 (second surface, R^2 = 66 %) for LV. For none of the subjects was the interaction first x second surface significant. Averaging the results for the two subjects, 20 % of the after-effect was accounted for by the first surface and 76 % by the second surface. Other preceding surfaces, e.g. from a previous trial, might explain the remaining 4 %.

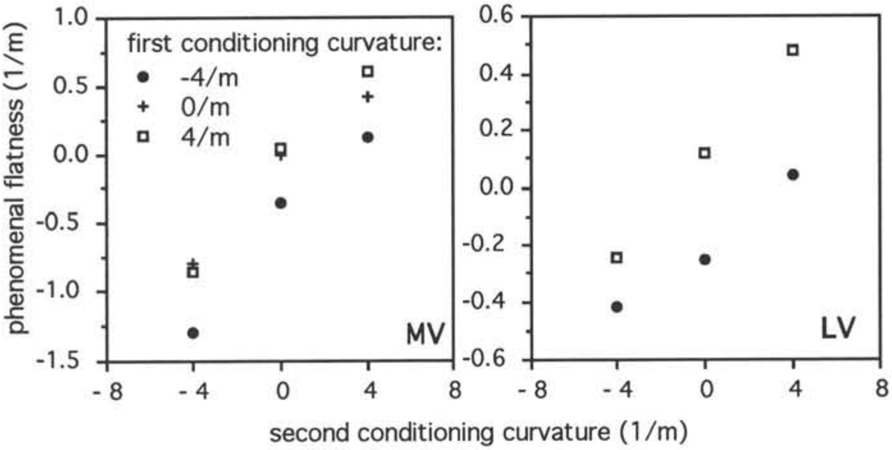

Figure 3: phenomenal flatness for all combinations of first and second conditioning curvature

Discussion and conclusion

We conclude that it is not only the most recently touched surface which can contribute to the value of the phenomenal flatness. In our case both preceding surfaces have influence. The contributions of these surfaces, however, are not equal. The last surface clearly has the stronger influence on the final haptic after-effect.

The decay rate of the after-effect of the first surface cannot be deduced from this experiment. However, the time constant cannot be infinite, otherwise the first surface would have had the same relative influence as the second surface, nor can it be close to zero, for the first surface actually has some influence.

Because of the unknown decay rate we cannot predict what the after-effect would be for different contact durations. So far we have assumed that the final after-effect in

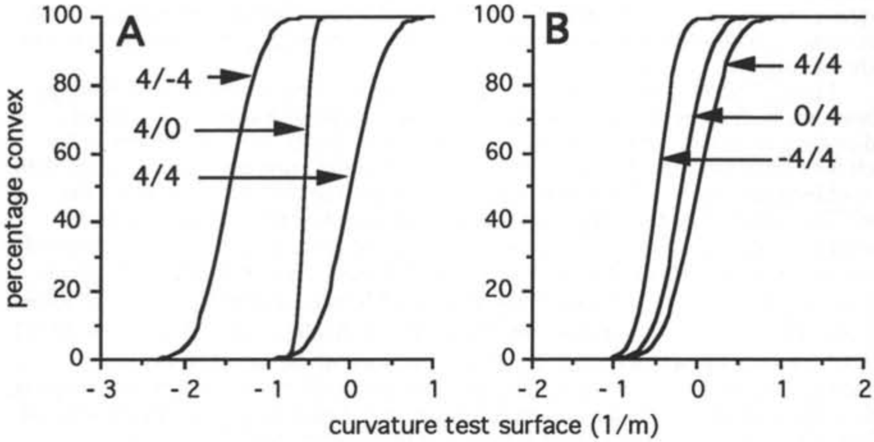

Figure 4: psychometric curves for combinations with A) constant first conditioning curvature and B) constant second conditioning curvature

the case of sequentially touched surfaces is a summation of the after-effect of each surface, which is the result of adaptation to the objective curvature. The decay rate possibly depends on the succeeding surface. More experiments are needed to find out whether this assumption is valid. For instance, it is also conceivable that one adapts to the subjective curvature, since the judged curvature of a surface is already influenced by the preceding surface. We believe that this issue can be decided empirically.

Acknowledgement

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Stability of Rhythmic Perception-Action Patterns in Children with Developmental Coordination Disorders

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Abstract

In this study, we investigated the stability of rhythmic perception-action patterns in children with Developmental Coordination Disorders (DCD) and matched controls by applying 'perceptual' perturbations, and by increasing the frequency of the patterns. Children with DCD showed longer relaxation times and lower critical frequencies compared to controls, indicating deviant pattern stability. These findings suggest that the poor rhythmic perceptuo-motor behaviour of children with DCD might be related to a lack of coordination stability of perception-action patterns.

Introduction

Children with Developmental Coordination Disorders (DCD) are characterized by a marked impairment in the development of motor coordination that is not due to mental retardation or to a known physical disorder (APA, 1987). One of the problems of DCD-children in the perceptuo-motor domain appears to be their timing control in rhythmic actions. It was found, for example, that the temporal variability of DCD-children in unimanual rhythmic finger tapping is larger compared to matched controls (Williams et al., 1992; Geuze & Kalverboer, 1987). Williams et al (1992) suggested that these timing problems are caused by a non-optimal function of central timekeeping processes that prescribe the timing and sequencing of movements in rhythmic actions.

In our research project, we investigate timing control in rhythmic actions from a dynamic systems perspective. Following such perspective, the timing in rhythmic coordinated actions emerges from intrinsic coordination dynamics, rather than being regulated by a central timekeeper. Theoretically, such dynamics are captured as equations of motion of relevant *collective variables*. The *relative phase* ϕ between two rhythmically moving units appears to be a relevant collective variable to describe interlimb coordination, or the coordination between a rhythmically moving limb and periodic perceptual events (Kelso et al., 1990; Kelso, 1994). Experimentally, signatures of relative phase dynamics can be found in the temporal *stability* of coordination patterns, which can be assessed through various stability measures, such as the time it takes to return to initial stability (i.e., relaxation time τ) after an experimentally applied perturbation, or the frequency where loss of stability occurs (i.e., critical frequency). In the experiment to be reported, we tested the stability of unimanual rhythmic perceptuo-motor patterns in DCD-children to investigate whether they show deviant pattern stability compared to matched controls. Such deviant stability might explain their timing problems in rhythmic perceptuo-motor behaviour. We applied 'perceptual' perturbations to measure τ, and manipulated the movement frequency to determine the critical frequency. We hypothesize that DCD-children will show (i) longer relaxation times, and (ii) loss of stability at a lower frequency in comparison to controls.

Experiment

Subjects

We selected 24 children with DCD and matched (age and sex) controls from 10 primary schools, using the Movement-ABC test battery (Henderson & Sugden, 1992) as a selection instrument (DCD < 15th percentile). Children were between 7- and 12-years of age.

Apparatus

A custom-made metal brace (length 8 cm), attached at the bottom end of a vertical rotation axis, was used to record flexion-extension movements of the index finger in a horizontal plane. A potentiometer was used to sample (100 Hz) continuous angular positions of flexion-extension movements. Visual stimuli (duration 125 ms) were displayed by two LED's (distance 12 cm) that were placed in the horizontal plane. The distance from the LED's to the rotation axis was 20 cm. A discrete visually specified rhythmic pattern was generated by a PC. Subjects were seated at a table. Their hand was holding a grip and the index finger was attached to the brace. The metacarpophalangeal joint of the index finger was placed coaxially under the vertical axis of rotation and the index finger could be pointed towards the LED's.

Procedure

Subjects were instructed to perform rhythmic flexion-extension movements of their index finger. The task was to coordinate the finger movements with the visually specified pattern in two different coordination modes: inphase and antiphase. The stability of these rhythmic perception-action patterns was tested in a perturbation condition and in a driving frequency condition.

Perturbation condition. Inphase coordination was requested. Each trial consisted of 60 left and right visual stimuli, corresponding with 30 movement cycles. Pacing frequency was set at 1 Hz. In each trial two perturbations were applied at the 9th and 21th stimulus. A perturbation consisted of a phase advance of the visual stimuli with $\phi = \frac{1}{4}\pi$ (250 ms). Subjects were instructed to 'catch up' with the visual stimuli as quick as possible. Subjects performed two practise trials and eight experimental trials.

Driving frequency condition. Subjects performed inphase and antiphase coordination tasks. Each trial consisted of 80 left and right visual stimuli (i.e., 40 movement cycles), starting at 1.0 Hz (8 movement cycli), and increasing with 0.05 Hz per two movement cycles to 1.8 Hz. Subjects performed one practise trial and four experimental trials in each coordination mode.

Data-analysis

Discrete estimates of the relative phase between the finger movements and the visual stimuli were calculated at maximum finger flexion and extension (i.e., two estimates per movement cycle). In the perturbation trials, relaxation time was defined as the time the relative phase returned to its initial stability range. In the driving condition trials, critical frequency was defined as the pacing frequency just before a loss of stability (i.e., a phase-switch or phase wandering) occurred.

Preliminary Results

Preliminary results of 6 DCD-children and matched controls will be presented. *Relaxation time*. A one-way ANOVA was applied on τ. A significant difference was found between DCD-children and controls, $F(1,5) = 10.55$, $p<.01$, revealing that DCD-children were slower in restoring initial stability (Figure 1, left panel).
Critical frequency. When subjects were prepared in the inphase coordination mode, the increase of frequency resulted eventually in phase-drift and wandering. When prepared in antiphase coordination, the increase of frequency often resulted in a phase-switch to inphase coordination, eventually followed by phase wandering. A 2 (group) X 2 (phase-mode) ANOVA was applied on critical frequency. DCD-children showed lower critical frequencies for in- and antiphase coordination patterns than controls (Figure 1, right panel), but this difference was only significant for the antiphase task, $F(1,5) = 4.48$, $p=.05$. No significant difference was found between the two phase-modes, however, an interaction effect for group X phase-mode revealed larger differences for DCD-children between phase-modes than controls.

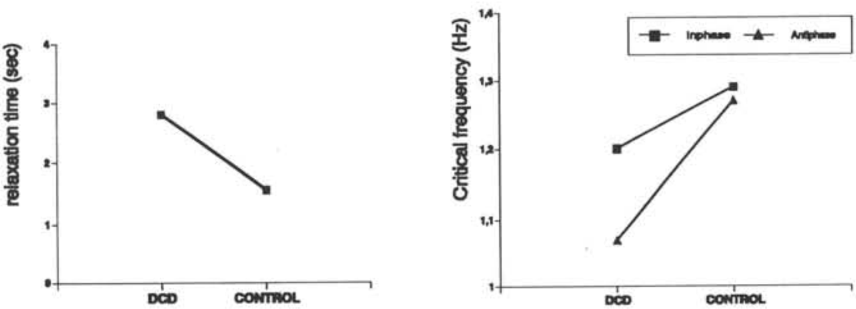

Figure 1. Mean group differences between DCD-children and matched controls for relaxation time τ (left panel) and for critical frequency (right panel).

Conclusion

DCD-children appeared to be slower in restoring stability of rhythmic inphase perceptuo-motor patterns after experimentally applied perturbations, which indicates that the coupling between their moving finger and the periodic visual events is less strong compared to controls. Also, the lower critical frequency for DCD-children shows that they loose pattern stability sooner when frequency constraints come into play. The finding that antiphase perceptuo-motor patterns are less stable than inphase patterns is in line with other empirical evidence (e.g. Kelso, et al. 1990). Interestingly, the difference between inphase and antiphase pattern stability in DCD-children is large compared to controls. Our findings show that DCD-children especially have problems with the antiphase coordination mode.

The stability features of rhythmic perceptuo-motor coordination patterns we described in this study (relaxation after perturbation, loss of stability) are hard to interpret following a central timekeeper perspective. The suggestion that problems in the timing control of rhythmic actions in DCD-children is a consequence of a central timekeeping deficit (Williams et al., 1992), therefore, has to be questioned here. Rather, our preliminary results suggest that their timing problem is due to a lack of coordination stability at a lower level of organization. DCD-children seem to have more difficulties in optimally tuning their relative phase dynamics to produce stable perceptuo-motor patterns than their peers.

Acknowledgement

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On Development to Prehension

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Abstract

The purpose of the experiment was to show that the developmental change from reaching without grasping to reaching with grasping during the first six months of life carried the characteristics of a discontinuous phase transition (catastrophe). A longitudinal-study was carried out with 10 infants, age 8 to 24 weeks. A cusp catastrophe model and a linear regression model were fitted to the data. The Likelihood-Ration test indicated that the likelihood of the cusp model was significantly higher ($p< .001$). The cusp model predicted that arm weight and arm circumference has the strongest influence on the control parameters.

Introduction

One of the earliest undisputed signs of goal-directed behavior is reaching towards and grasping an object of interest, a skill that generally develops between 3 and 6 months of age. Several suggestions have been put forward as to how to account for the development of this skill. One hypothesis is that the change from reaching without to reaching with grasping can be understood as a so-called phase transition or catastrophe.

Gilmore (1981) described eight criteria by which abrupt changes can be classified as discontinuous phase transitions (or catastrophes). He called these criteria "catastrophe flags". Five of them, namely, bimodality, inaccessibility, sudden jumps, hysteresis and divergence appear simultaneously when a system is in transition. The other three, namely, anomalous variance, critical slowing down and divergence of linear response can be found prior to a transition, and therefore signal an upcoming transition. Recently, evidence has been found for three catastrophe flags (Gilmore, 1981) in the development of prehension (Wimmers, Savelsbergh, Beek & Hopkins, 1996). Evidence was found for the occurrence of a sudden jump from reaching without grasping to reaching with grasping. Furthermore, evidence was found for bimodality and inaccessibility. From these results it can be argued that a cusp model is a candidate model for the found transition. Subsequently, we modeled this transition as a cusp model by a method of Cobb (1980, 1981).

A cusp model is one of the elementary catastrophes identified by Thom (1975), in which a transition is defined as a sudden change in a behavioral variable induced by a small and continuous change in an independent variable or control parameter. Although the control parameter is entirely unspecific to the resulting pattern, its manipulation is instrumental in creating a new order at the macroscopic level. It controls in the sense of leading the system through its respective states of equilibrium.

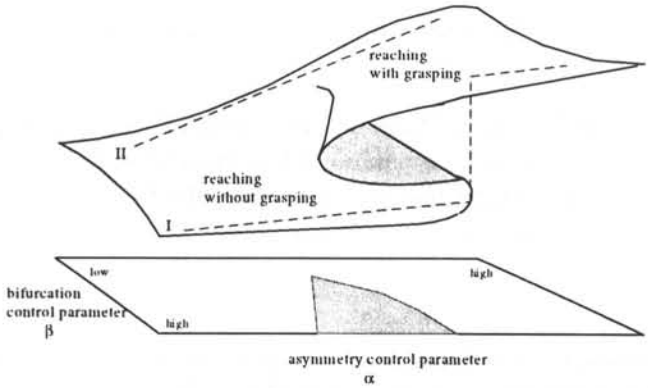

Figure 1. A cusp model of the development of prehension

In a cusp model, the transition between two behavioral states of a unidimensional behavioral variable is governed by two control parameters. To model the cusp, a cusp function

$$V_{(x)} = - \tfrac{1}{4} x^4 + \tfrac{1}{2} \beta x^2 + \alpha x \qquad (1)$$

is used where x is the behavioral variable, α and β, respectively the asymmetry and bifurcation control parameter. By changing the control parameters of the cusp function, the number of minima of the function changes. The minima of the cusp function corresponds with stable equilibrium states of the behavioral variable. The minima can be calculated by taking the first derivative of the cusp function

$$V'_{(x)} = -x^3 + \beta x + \alpha = 0 \qquad (2)$$

the solutions of which give us the cusp surface drawn in Figure 1.

Method

A cusp model was fitted to longitudinal data from 10 infants, age 8 to 24 weeks. As for potential control parameters, we tested the following independent variables: a) arm length, b) arm circumference, c) arm volume, and d) arm weight.
The form of the cusp surface in raw score form is

$$-\left(\frac{x-\lambda}{\sigma}\right)^3 + \beta\left(\frac{x-\lambda}{\sigma}\right) + \alpha = 0 \qquad (3)$$

$$\alpha = (\alpha_0 + \alpha_1 a + \alpha_2 b + \alpha_3 c + \alpha_4 d),$$
$$\beta = (\beta_0 + \beta_1 a + \beta_2 b + \beta_3 c + \beta_4 d)$$

In Equation (3), x is the behavioral variable, α and β the control parameters, a to d the independent variables with a weight factor α, σ, and λ the scale and position of the catastrophe process. The weight factors provide us the opportunity to evaluate each independent variable used in the model in their contribution to the control parameter.

The analysis program, which used the algorithm of Cobb, performs the calculation by means of the maximum likelihood method necessary to provide the values for Equation 3. A correlation coefficient is calculated for the cusp, which is the proportion of the variance accounted for by the model if the nearest mode is used as the predicted value of x. Because of the latest problem it is only an approximation and therefore called pseudo-R^2.

To test whether the cusp model is the best model for the data, it is compared with a linear model. To find the best fitting model, R^2 and log likelihood are determined for a linear- and the cusp model. As the R^2 for the cusp model is a pseudo-R^2 it cannot be applied for hypothesis testing. The log likelihood, however can be used to compare the linear and the cusp model by means of a χ^2 -test.

Results and conclusion

The calculated best-fitting cusp plane is described by:

$$-\left(\frac{x-.51}{.27}\right)^3 + \beta\left(\frac{x-.51}{.27}\right) + \alpha = 0$$

$$\alpha = -20.17 - .04a + 1.36b - .0034c + 13.46d$$

$$\beta = -11.11 + .59a + 1.03b + .0012c - .5120d$$

The pseudo-R^2 for this model is .61, the log likelihood -100.44. For the calculated linear model the values are .64 and -272.04, respectively. The difference between the log likelihood is significant, $\chi^2(6) = 343.21$, $p < .001$, yielding a statistically better fit for the cusp model.

In this case we can say that the cusp model fitted the data better than a linear model and that the change from reaching without grasping to reaching followed with a grasp contained a discontinuous phase transition. From the standardized weight factors it is predicted that arm weight and arm circumference has the strongest influence on the control parameters.

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