Anticipating behaviour in supervisory vehicle control

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in supervisory vehicle control

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Preface

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I dedicate this work to Mimi and the girls who had so much patience, and to my parents.
Chapter 1

Introduction

Background

The human’s task in process control is changing rapidly. Until the last decade, the human operator was primarily involved in manual control of single processes and to a certain extent in supervising automated stand alone systems. Today, automated control systems are applied on a large scale with a considerable change in operator tasks. The role of the operator as a direct controller has been transformed into that of a supervisor who is monitoring a process controlled by semi-intelligent subsystems, and that of a manager who is performing additional planning and decision making activities. In this supervisory control role the operator, who may also directly observe the process itself, interacts with automated systems that themselves encompass autonomous control loops with the controlled process through actuators and sensors. The operator specifies the goals, constraints and procedures in terms of setpoint changes (process tuning actions) for the automated systems rather than controlling the process directly. Sheridan (1992) compares this computer-mediated control situation with a manager interacting with subordinate staff members in a hierarchical organisation. The manager gives directives that are understood and translated into detailed actions by his staff. In turn, the subordinates collect detailed information about results and present it in a summarised form to the supervisor, who must determine the state of the system in order to make the proper decisions to reach the desired goals.

In the supervisory control situation, the computer system transforms information from the operator to the controlled process and from the controlled process to the operator, while at the same time the computer system closes control loops with the process, thus making the computer a more or less autonomous controller. Situations exist where the operator directly observes the process state, for instance a navigator observing the movements of his automatically controlled vessel with respect to the environment. In other situations displays are used to inform the operator about the current state of the process and about the future plans.

Humans have limitations, particularly when they monitor slowly responding systems. When they cannot immediately see the result of a control action, they have difficulties in understanding the functioning of the underlying process. They are not able to
accurately generate future process state information based on their perception of changes in the process state (Wagenaar & Sagaria, 1975; Wickens, 1986). Moreover, predictions may impose considerable cognitive workload (Johannsen et al., 1979). For accurate control it is essential that operators be able to correctly anticipate process responses in order to prevent control errors due to time lags. Correct anticipation requires knowledge of the goals, the process characteristics and the disturbances that may act on the system, and consideration of the current control actions and observed changes in the process state. It is known that operators may learn rules to predict process changes, however, these rules may not be valid in unexpected task conditions (Broadbent, Fitzgerald & Broadbent, 1986). Schuffel (1986) showed that knowledge of control-effect relationships in ship control is rather inaccurate.

Computer systems can to a large extent compensate for these human limitations in supervisory control. In particular, computers can help operators to better understand the process by displaying the appropriate information. This will be accompanied by advice about effective input commands for control and an increased knowledge of the stochastic nature of the disturbances. Kelley (1968), McLane & Wolf (1965), Kraiss (1980), and Wickens (1992) indicated that control performance improves by having a computer perform calculations to predict the future state of the controlled process. Information that predicts the future state of a process, has become particularly important as an aid to improve the controllability of slowly responding processes, i.e., processes characterised by the fact that control actions given at one time will not effectively alter the process state until some time (often minutes) later. An example in ship control is the use of path prediction for guiding a large vessel in a narrow fairway along a planned route (Bernotat & Witlof, 1965; Berlekom, 1977). Path prediction information, showing the track ahead of the controlled vessel on a navigation display, may be very helpful in routine task conditions, i.e., task conditions where operator's activities are mainly controlled by a set of rules that have proven to be successful. Accurate control is then obtained as long as the navigator matches the predicted track ahead with the planned route by responding to the predicted error rather than to the current error. In particular in conditions where the planned route is known in advance this task is a well-defined tracking task (Schuffel, 1986). Note that this is only true when the path predictor is accurate and the future disturbances acting on the vessel are known. In non-routine task conditions, however, no match or only a partial match exists between the actual situation and the past experience. Proven rules are not available in those circumstances. For instance, there may be a mismatch between the predicted track ahead and the planned route:

- Due to disturbances that vary in time and space, or due to inaccuracy of the prediction itself
- Due to a sudden failure in one of the subsystems that may cause the controlled process to respond differently

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- Or, there may be a sudden change in the immediate goal, for instance when the fairway is partly blocked so that an alternative route must be chosen.

Lee & Moray (1992) suggest that experienced operators, who have fixed control strategies that rely upon feed-forward manual control and fixed allocation of automated control, will switch back to exploratory behaviour (feedback control) as soon as a fault occurs, while they try different means of control to maintain system performance. Human behaviour may then be goal-controlled in a sense that different attempts are made to reach the goal, and that a sequence of actions thought to be successful is selected. In such a problem solving exercise, an internal representation of the process properties and of the environment is used. Kelley (1968) describes the conception of goals as predicting (envisioning) possible future states of a controlled variable, (i) if nothing is done to affect it, and (ii) if certain of the available control actions are taken. Unfortunately, operators generally have a poor internal representation of higher-order non-linear dynamic systems (Schuffel, 1986; Schraagen, 1994; Diehl & Serman, 1995; Endsley & Kiris, 1995), causing loss of controllability. Adequate operator support should therefore show the predicted process state relative to the goal as a consequence of multiple process tuning actions.

In summary, there is no sufficient understanding of anticipating behaviour in mainly non-routine task conditions. It is not known exactly what the requirements are for predictive information to effectively improve anticipating behaviour in non-routine task conditions. In routine task conditions, accurate supervisory control is obtained by using path prediction information. Kelley (1968) suggested that an effective support system in non-routine task conditions should consider a range of process tuning actions and show a domain of predicted states of the controlled process. Such a technique was supposed to enable the operator to select the best solution by applying basic rules for keeping the controlled process within its specified target domain in all circumstances. The support system based on this technique should identify eventual disturbances as well.

In the present study a series of man-in-the-loop simulator experiments is presented. Participating test subjects were requested to perform specific supervisory control tasks using different anticipation support systems. Task performance was measured in different task conditions, created by generating scenarios of different complexities in the simulator. By investigating the operator's supervisory control behaviour with respect to perception, interpretation, and effectuation, expectations on effectiveness of computer support were tested.
Chapter 1

Supervisory vehicle control

Functions
Control functions indicate activities that must be undertaken in order to accomplish the system's goals. With regard to vehicle control, Sheridan (1992) proposed a hierarchy of functions. Figure 1.1 shows a hierarchal structure consisting of a set of control loops; each inner loop has a setpoint determined by its next outer loop. The innermost loop represents the typical control function. For aircraft this is primarily pitch and yaw control to compensate for air turbulence and crosswinds; for ships this is primarily heading control to compensate for tidal currents and crosswinds. Operators are mainly involved in compensatory tracking, where they observe the magnitude of the control error with respect to the current state of a controlled variable, trying to compensate for this error (Poulton, 1974). The intermediate loop represents the guidance function where the short-term progress of the voyage is monitored and controlled. For instance, when a pilot turns into a runway approach glide-path while checking the planned route, airspeed, altitude, and thrust. Or, when a ship enters restricted waters and the mate is checking the ship's position relative to the planned route, the aids to navigation, the ship's speed and thrust, and nearby ship traffic. Operators are mainly involved in pursuit tracking, where they observe the target state and the current state of a controlled variable, trying to minimise deviations between these two states. The outer loop represents the navigation function, where planning and decision making is performed, or as Kelley (1968) stated, where plan conception and plan selections are made. A ship's master selects the route, determines the waypoints, and maintains the overall view of the ship's state.

![Diagram showing the hierarchy of supervisory control of vehicles](image)

Figure 1.1 The hierarchy of supervisory control of vehicles shows the navigation, guidance and control functions as nested loops. These functions describe activities that must be performed in order to achieve the desired system goals (adapted from Sheridan, 1992).
Human involvement

Control of the three hierarchically structured functions is mainly allocated to automatic equipment. The role of the human is to supervise the state of the process and the performance of the automated control systems. In this respect, Sheridan (1980, 1992) distinguished planning, monitoring and task interpretation, process tuning and intervention, as well as fault management, to be the primary human activities. The operator specifies the goals, constraints, and procedures for execution; and is the responsible planner and decision maker who is interpreting information of the system performance under automated control. The operator intervenes when deviations occur from the planned system state, or when a malfunction occurs, by changing the setpoints of the automated controllers. The operator retains the option in all three loops taking over control when this is needed or desired. Overall control performance depends on the ability of the operator to foresee future deviations, i.e., the ability to anticipate.

The current study focuses on the use of automated systems to support anticipation in supervisory control tasks. Automation is generally considered a cost-effective replacement of the human operator because suitable equipment may be used to perform functions for which the human operator is unsuited. Many engineers see automation as the best opportunity to increase system performance and safety, and to remove human error at its source by replacing fallible operators by virtually unerring machines. Bainbridge (1989), Parasuraman, Molloy & Singh (1993), Wiener & Curry (1980), Wiener (1988), however, emphasize that there are also negative sides to automation. For instance, automation seems to facilitate other types of human error, e.g., decreased task involvement may lead to a lower level of vigilance and loss of skills. It is also found that automatic equipment does not always meet its expectations in reducing mental workload or increasing system performance. Since it is the primary goal of automation to enhance both the well-being of the operator, to optimise operator workload, to improve the total system performance, and to lower the costs (AGARD, 1984; Boff & Lincoln, 1988), the main question remains which of the functions may be entirely or partially taken over by automated systems, and what type of information is required for best interaction, improving supervisory control performance.

The control function, as far as human supervisory control is concerned, mainly applies to automatic skills. Task performance at this level is mainly of a closed-loop character. In general, control activities take place without conscious control as smooth, automated, and highly integrated patterns. Activities may be considered a sequence of skilled actions composed for the actual occasion as habitual routines. Only occasionally, performance is based on feedback control, where responses are generated to the observation of an error
signal representing the difference between the actual state and the planned state in a time-space environment, and where the control signal is derived at a specific point in time. A typical example is riding a bicycle using largely automatic behaviour. Sensors are eyes, ears, vestibular and kinesthetic receptors. Stimuli are referred to as continuous quantitative sensed information about the time-space behaviour of the environment. When there is a major deviation from the planned route, the polarity and the magnitude of that deviation are estimated, leading to additional control activities to compensate for the deviation.

The guidance function applies to the use of information about future values of the controlled variables. Task performance at this level is pursuit tracking. Activities concern familiar work situations, where routine task conditions exist, requiring more or less automatic stimulus-response control behaviour, largely based on the application of proven rules empirically derived from previous successful experiences. No major errors occur and actions are more or less pre-programmed. First, the course of the stimulus (forcing function) must be determined based on preview information. In the case of ship control, the route to be followed is inferred — given certain goals that must be achieved — by observing the course of the fairway and by observing the steady state traffic situation. Full preview means that the forcing function is known at a glance. In addition, information is gathered for anticipation, i.e., to predict future tracking errors. Ship navigators may have difficulties anticipating, particularly in conditions where slow responding ships are controlled. Although the radar system shows speed and position information of the controlled vessel and of all adjacent ships on a plan-view display, it is difficult to predict accurately the manoeuvring behaviour of the controlled vessel, and to assess relative movements of the adjacent ships. Therefore, specific aiding systems are used to extrapolate movement information and to predict collision risk. It has been recognised that humans are not very good at system monitoring and at detecting infrequent signals. On the basis of human performance models it was concluded that too many factors seem to influence monitoring strategy. This hampers optimal sampling behaviour due to, e.g., uncertainty of the data, uncertainty by forgetting, probability of missing critical events, cost of making an observation (Kvalseth, 1977; Moray, 1986; Sheridan & Johannsen, 1976; Van Delft, 1986, 1997). In this respect, Reason (1990) argued that human behaviour at this level may be associated with misapplication of good rules and application of bad rules. Decision making and handling at the guidance level consists of selecting new reference values for control, for example, to select a new setpoint for the course controller.

In the navigation function, human supervisory activities are goal-controlled and based on knowledge of the task situation. Task performance at this level is open-loop; the consequences of control actions are only known after a considerable period of time. Activities concern unfamiliar situations in non-routine task conditions, where, due to unexpected events, proven rules are not available, and where task execution is based on
knowledge of the controlled process in a new task situation. Operators act as managers when task definitions are not fixed and human creativity is explicitly required. First, plans to solve the problem situation are generated and tested against the system goal. In that case, information is gathered to assess long-term effects of short-term decisions. For instance, what are the consequences when a planned route is altered due to bad weather conditions ahead? What is the effect of different route alternatives on destination arrival time, fuel consumption, weather routing, cargo handling, watch keeping sequences, and costs? These questions were dealt with when the voyage was planned on departure, but these questions rise again when unexpected events occur. An automated system may have failed, or, other ships suddenly change course, increasing collision risk. Here, alternatives are generated in a mental exercise, and judged against criteria for safety and efficiency. To select the best alternative, the problem of the new task situation is analysed in detail and solved on the basis of anticipation. The criticality of non-routine task conditions is related to the fact that there is only a partial match between the actual situation and the past experiences. Operators cannot use firm rules to perform the task. Laboratory studies have indicated that performance is sub-optimal in these circumstances. For instance, Schuffel (1986) found in simulator studies on human control of ships that subjects, even after instruction, are incapable of selecting the proper rudder deflection in open-loop control tasks. Schraagen (1994) found comparable results in an observation study; river pilots seem to exploit specific references (e.g., pile moorings, buoys and leading lines) for checking the ship’s position and orientation in a particular area rather than being able to accurately predict a ship’s future position and orientation. In an earlier study, Papenhuijzen & Stassen (1989) found comparable results. In this respect, Diehl and Sterman (1995) stated that human cognitive capabilities do not include the ability to intuitively solve systems of higher-order nonlinear differential equations. Operators who are monitoring automated systems, are operating in a partial out-of-the-loop situation. Satchell (1993) calls this the peripheralisation phenomenon; humans are shifted from being in direct contact with the process to being a system manager. This may, in general, cause two adverse effects: Loss of manual skills, and loss of awareness of the controlled process state (Endsley & Kiris, 1995). Reason (1990) distinguished two main factors underlying mistakes at this level which may have great impact in systems with a high level of complexity: bounded rationality, and the fact that knowledge relevant to the problem is nearly always incomplete and often inaccurate. The operator who is acting as a manager interacts with the system at a higher level without knowing system performance at a detailed level which may increase the distance between the operator and the controlled system and lead to sub-optimal decision making under critical circumstances (Satchell, 1993). More time may be needed to get back into the loop again, time which the critical situation may not allow.
In the current study, a hypothetical framework is used to characterize operator involvement in fulfilling the three functions of control through three different stages of human information processing behaviour (Rasmussen, 1986; Schuffel, 1992; Endsley, 1988): perception, mental processing (interpretation and planning), and effectuation (decision making and handling). The basis of this framework is formed by a person’s perception, identification and recognition of relevant elements in the environment, as determined from displays or directly by the senses. Interpretation by mental information processing mechanisms is the second stage, followed by effectuation, i.e., action selection and motor control based on decisions. Table 1.1 summarizes human involvement in the fulfilment of vehicle control functions, showing that each behavioural element affects each function.

Table 1.1 A hypothetical framework of human involvement in hierarchically structured vehicle control functions. By labelling the supervisory control functions (N, G, C) and the operator’s stages of information processing behaviour (P, I, E), an interaction matrix is composed (N.P through C.E). This matrix forms the basis of the current study.

<table>
<thead>
<tr>
<th>Functions</th>
<th>Stages of information processing behaviour</th>
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<tbody>
<tr>
<td>Navigate</td>
<td>Perception N.P</td>
</tr>
<tr>
<td></td>
<td>Interpretation N.I</td>
</tr>
<tr>
<td></td>
<td>Effectuation N.E</td>
</tr>
<tr>
<td>Guide</td>
<td>Perception G.P</td>
</tr>
<tr>
<td></td>
<td>Interpretation G.I</td>
</tr>
<tr>
<td></td>
<td>Effectuation G.E</td>
</tr>
<tr>
<td>Control</td>
<td>Perception C.P</td>
</tr>
<tr>
<td></td>
<td>Interpretation C.I</td>
</tr>
<tr>
<td></td>
<td>Effectuation C.E</td>
</tr>
</tbody>
</table>

The literature reports models describing human involvement in control functions (Pew & Baron, 1982; Johannsen, 1988; McMillan et al., 1989). These models describe human performance, in a wide range of task, from daily routine to stressed encounters with incidents. It is the intention to use these models for reliable prediction of human performance and human error modes. These models may also be used to obtain more insight in elements that may affect control performance, and should be considered in the design of automated support systems for supervisory control.

Two such models are mentioned here. The first by Rasmussen (1983, 1986) proposed three hierarchical levels of human information processing behaviour:

- Target oriented skill-based behaviour at the lowest level
- Procedure oriented rule-based behaviour at the intermediate level
- Goal controlled knowledge-based behaviour at the highest level.

Skill-based behaviour represents well-learned sensory-motor performance in continuous manual control tasks in stationary conditions. In general, human activities can be considered as a sequence of skilled activities assembled for a specific situation. The flexibility of skilled performance comes from the ability to assemble, from a large reper-
toire of automated subroutines, sets suited for specific purposes. Rule-based behaviour represents performance consciously controlled by a set of stored rules or procedures. This is the case with monitoring and interpreting tasks, that is, first patterns are recognised on the basis of explicit know-how from familiar situations, then ‘if-then-rules’ are triggered before executing the appropriate response. Knowledge-based behaviour encompasses planning and management tasks, requiring situation assessment of unfamiliar situations for which no rules for control are available from previous encounters and the consideration of alternative actions at a strategic level. When we convey Rasmussen’s model to the control function descriptions above, it is stated that control functions (C) mainly require skill-based behaviour, that guidance functions (G) mainly require rule-based behaviour, and that navigation functions (N) mainly require knowledge-based behaviour.

The second model by Schuffel (1986) uses a different approach to describe human behaviour (G, C). He used Adams’ (1971) closed-loop theory and Schmidt’s (1982) schema theory to hypothesize that a ship handler develops a motor memory (pre-programmed control) and a perceptual memory (feedback control). A motor memory contains the relationships between initial conditions, desired and past outcomes, and rudder deflections; in fact, a motor memory describes a cognitive motor program that determines initial control actions of the operator. A perceptual memory contains the relationship between initial conditions, past system outcomes and perceived ship movements. In this case, a perceptual memory is considered to be a reference trace, based on the storage of past movements of the vessel. Starting a movement also starts an anticipatory activation of the perceptual trace, which is compared with feedback information about ongoing movement of the vessel. The strength of the perceptual trace grows as a function of the experienced feedback, which reveals the future tracking error for the operator, providing the opportunity for anticipation. Schuffel also distinguishes slow and rapid task conditions:

- In slow movement tasks, control behaviour is based on perceptual memory and on motor memory
- In rapid movement tasks control behaviour is based on a motor memory only.

Experimental results show that mariners perform tracking tasks primarily on the basis of feedback and only a rough motor memory is developed.

Other models are based on control theory and describe the characteristics of human behaviour in vehicle control. These mathematical models are frequently used to generate and analyse performance data concerning simulated operators involved in a simulated process.

Models describing the execution of control functions (C) are models that describe an operator performing a manual ‘in-the-loop’ control task. A well-known example is the Cross-Over Model, of which a schematic representation is shown in Figure 1.2 (McRuer &
Krendel, 1974). The model combines the controlled system and the human operator by using the transfer function of the open loop. The underlying assumption of this approach is that the model of a well-trained and well-motivated controller adapts to the dynamics of the controlled process in such a way that the open loop transfer function meets the stability considerations in terms of amplitude and phase margins, for the closed-loop system. The Cross-Over Model proved to be successful in describing the influence of system dynamics on human performance, e.g., to know if a planned aircraft will be flyable with a certain set of aero-flight dynamics (McRuer & Jex, 1967). The model is accurate because it describes human system behaviour that is fairly constrained, however, it must be emphasized that the model is limited; its parameters are based purely upon fits to the input-output relations for tracking.

Figure 1.2 A schematic representation of the Cross-Over Model developed by McRuer & Krendel (1974). They found that the open-loop transfer function for proportional, first order, and second order process characteristics could be represented by an integrator, gain and time delay, expressed by the equation

\[
\hat{H}(\omega) = G(\omega)H(\omega) = \frac{\omega_c}{j\omega} e^{-j\omega \tau},
\]

where the operator control behaviour is represented by a describing function \(G(\omega)\) including a remnant \(N(\omega)\), and where \(H(\omega)\) is the function describing the dynamics of the controlled process, \(\tau\), the time delay, \(\omega\) the radial frequency, and \(\omega_c\) the cross-over frequency. Allowing for the stability requirements of positive gain margin and phase margin, this open-loop transfer function makes the amplitude ratio of the open-loop frequency response very large over the frequency range of the input bandwidth (accurate closed-loop transfer), and very small outside this range (stable closed-loop transfer).
To overcome the limited applicability of the Cross-Over Model, Baron & Kleinman (1969), Kleinman, Baron & Levison (1971) developed the so-called Optimal Control Model. In contrast to the Cross-Over Model, the Optimal Control Model describes system behaviour in the time domain. The model is based on the assumption that the human operator acts as an optimal controller, taking into account the inherent human limitations such as processing time, inaccurate observation, inaccurate generation of system output, and limb dynamics. It therefore assumes that the human operator has a perfect knowledge of the system dynamics and the stochastic nature of the disturbances. Principle elements are a state-estimator (Kalman filter) that provides a best estimate of the controlled process states, a predictor that compensates for the human's inherent cognitive data processing delay, and an optimal controller (optimal gain matrix). The model appeared to be capable in predicting pilot performance in quite a number of well-structured task conditions, e.g., for flight control tasks, landing approach planning tasks, and aircraft hovering tasks (Baron, 1984). However, Baron also claims that the model does not include discrete tasks that are part of procedural activities. According to Rasmussen (1986), the computational complexity of the model, as well as the greater number of parameters that must be specified, may limit its applicability.

Veldhuyzen & Stassen (1977) described helmsman's control behaviour with a non-linear model that included an internal model of the controlled system and of the task to be performed. A phase plane type method was used (in terms of course error and rate of turn) to discriminate the different control strategies, as well as a predictive element to estimate the future course error. This model concept has shown to be well applicable in relatively simple course keeping tasks, but the model was not valid for describing rule-based behaviour, e.g., for describing control behaviour while manoeuvring in confined waters (Stassen, 1987).

Models describing the execution of guidance functions (G) need more than a description of a human servo mechanism. Pew & Baron (1982) indicated that a mental representation of the environment or system in which the performance takes place should be added. In terms of control theory this means that to describe human behaviour at least an internal model of the task, the system to be supervised, and the disturbances acting on the system must be included. In this respect, the Optimal Control Model was extended (Baron, Muralidharan, Lancraft & Zacharias, 1980) by providing a framework which allows modelling discrete and continuous tasks in a multi-operator environment; the PRocedure-Oriented CREw model (PROCERU). This model was typically developed to analyse aircraft crew procedures. The more knowledge based behaviour is involved in supervisory control tasks, the more of the operator's creativity and intelligence is required. Stassen et al. (1990) argue that "the overall task at this level consists of a number of subtasks, that is, monitoring, interpreting,
teaching; i.e., setpoint control or process tuning, planning, fault management, and intervention. Supervisory control tasks are more or less globally defined, leaving the operator a lot of freedom to choose a strategy in reaching the goal" (p. 813). The fact that decision making is involved complicates the description of human supervisory behaviour at this level. Because investigations in this field are complex and time-consuming, only a limited number of human supervisory models have been reported (Sheridan, 1992; Wickens, 1992).

In the field of human vehicle control, a number of studies are reported describing skill-based behaviour and rule-based behaviour in vehicle control. These models were characterised by modules representing the immediate environment of the control task. For example, Blaauw (1984) developed a Supervisory Driver Model based on the Optimal Control Model, reflecting manual control aspects, and the Optimal Control Decision Model (Kok & Van Wijk, 1978; Kok & Stassen, 1980), reflecting supervisory control aspects. A so-called observation/prediction block was used, representing knowledge about the controlled system characteristics, as well as the lead variables, i.e., the road to be followed, and the disturbances. Godthelp (1984) used a prediction model based on the so-called Time-to-Line-Crossing concept for describing driver’s anticipating behaviour, i.e., the time necessary for any part of the controlled vehicle to reach the edgeline of a driving lane. Van der Horst (1990) described driver’s anticipating behaviour during intersection approach in terms of time measures, such as Time-To-Intersection and Time-To-Collision. A minimum value of 1.5 s was used as a criterion for normal and critical encounters. In the maritime field, a human operator model of a navigator was developed that included a representation of the environment consisting of a state estimation model, a track planning, and a track following model (Papenhuijzen, 1994; Papenhuijzen & Stassen, 1989). In this model it was assumed that, from time to time, future states were predicted, and related to the perception of safety as determined by the track planning component. If necessary, a control action was carried out. Papenhuijzen followed a control theoretic and a fuzzy set approach, the latter being an approach using techniques that enable the conversion of a linguistic control strategy, based on expert knowledge, into an automatic control strategy (Zadeh, 1973). The model appeared to be successful when single ship task conditions were considered. Papenhuijzen concluded that the control theoretic model approach has better prospects than the fuzzy set model approach, due to the fact that the control theoretic model approach provides better insight in the functioning of the model, but it does not produce the most realistic rudder control output. Future improvements of this model include more realistic control and engine settings, the execution of more complicated navigation tasks in a time-varying environment, and complicated traffic handling.

Models describing the execution of navigation functions (N) require a description that includes both an internal representation of the environment and a description of human
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strategies, i.e., planning and high-level decision making. Attempts have been made to use production systems, borrowed from artificial intelligence techniques, and by investigating complex decision making processes through simulation (Bersini, Cacciabue & Mancini, 1988; Corker & Pisinach, 1995). Unfortunately, these models are not generally applicable. For instance, validity only exists in flight crew or air traffic control tasks, and, the models lack micro-behaviour accuracy due to validation problems. Stassen et al. (1990) and Johanssen, Levis & Stassen (1994) argue that modelling knowledge-based behaviour, which requires a description of human creativity and intelligence, sounds contradictory because it has to be considered as an attempt to replace knowledge-based behaviour by rule-based behaviour.

In summary, model studies have shown that human performance in control and guidance functions is based on knowledge of the controlled process and its disturbance, and on a mental representation of the environment. For example, early models developed by Kok & Stassen (1980), Godthelp (1984), Schuffel (1986), and Van der Horst (1990), describing human performance in fairly restricted (routine) guidance and control functions, included a representation of knowledge of the controlled system characteristics and the route to be followed. A later model developed by Papenhuijzen (1994) also included predictions of the future states of the controlled process as well as track planning and track following elements, which enabled this model to be used to describe human performance in certain (non-routine) navigation functions. Effective support systems for supervisory vehicle control should therefore address these elements individually. This is explained in the next Chapter.

Supporting supervisory vehicle control

In supervisory control systems, human operators interact with the controlled process through a Human-Machine Interface (HUMIF). HUMIFs are designed to support the operator in gathering relevant information through display systems, and in enabling the operator to control the system and to verify the system’s state relative to the outside world. HUMIFs must guarantee observability and controllability of the process, for the specific operator and system tasks. Task allocation depends on the capabilities and limitations of both the human operator and the controlled system. A HUMIF design consists of both physical and human information processing aspects, i.e., the design and layout of controls and displays, and the information content and representation. As machines have become more intelligent, much of the interface design is focussed on information gathering, interpretation, planning, and decision making components of the human-machine dialogue.
Chapter 1

In this respect, Endsley (1995) stated that HUMIFs must present the necessary information in a degree to which they are compatible with basic human cognitive abilities. A well-designed HUMIF results in optimal overall performance of the system, this means, maximum performance is obtained whereas mental workload remains within acceptable limits; the designer therefore has to consider the user’s capacity and limitations for information processing as well as task requirements (Veltman, 1991, Veltman & Gaillard, 1993). Stassen, Johannsen & Moray (1990) defined the term optimal performance as the performance that, according to certain cost criteria, leads to a best balance between process economy, safety and product quality. They state that it is not a minimal mental load that is required in that situation, but a preferred mental load.

Support of the control function (C) mainly concerns automated systems performing closed-loop control without prediction, i.e., autonomous control loops are formed with the controlled process. Many technical solutions exist in which automated systems can do a better job than human operators. For example, in ship control, applications are widespread where automated systems are used to keep the ship’s state variables at a predetermined value while compensating for environmental disturbances, e.g., a speed controller to maintain the ship’s speed at a predetermined value, or a track controller for keeping the ship on a predetermined route (C.P; C.I). In a supervisory control situation, these automated systems may be addressed by setpoint control, i.e., the operator performs process tuning actions only to compensate for errors by selecting a new reference value of the controlled variable (C.E). The current state of automation permits this level (area C) to be fully automated.

Support of the guidance function (G) concerns support of closed-loop control with prediction. As was mentioned earlier, preview information is essential to enable perception, detection, and recognition of the course of the stimulus, and consists primarily of a representation of the planned route. Current computer graphics systems provide technical means to present such information by depicting planned route and waypoint information on an electronic chart or radar display (G.P). Preview information is essential when a relatively high-frequency responding system is controlled. These are task conditions where the controlled system responds quickly with respect to the course of the planned route, given the actual speed of the vehicle. Predictive information, that is, information that shows the future state of the process which enables the assessment of future tracking errors, is particularly important in conditions where the controlled system responds slowly with respect to the course of the planned route (G.I). In ship control, technical solutions are provided by computer systems that enable calculation of the future track ahead of a vessel — so-called path prediction — facilitating the detection of deviations between the planned route
and the predicted track ahead (G.I). In the event of significant deviations, new reference values are selected (G.E) for control (C), e.g., a new setpoint value for the course controller.

Path prediction is a computer-based calculation of the future track ahead of a vehicle based on a single process tuning action, given the actual state, the control signals, the vehicle dynamics, and the disturbances, while showing a representation of the calculated predicted track ahead on a display. In the calculation, certain assumptions are made concerning the operator’s future control activities, e.g., that the operator keeps the control signal at its current value for a certain amount of time, and, that the future disturbances remain the same. The accuracy of the prediction is a function of the accuracy of the predictive algorithm and the accuracy with which actual state information of the controlled platform is obtained. Earlier studies revealed that human control of slow-responding systems may be improved when predictive information is used. Bernotat & Witlok (1965), and Berlekom (1977) investigated path predictors for ships, based on extrapolation; Kelley (1968), McLane & Wolf (1965) showed positive effects of path prediction on navigational accuracy, and on the learning of ship control tasks. Also Pew (1966), Bertsche & Cooper (1979), and Hayes (1979) argued that path prediction based on speed vectors could enhance ship control accuracy. Although these studies pointed out in a quantitative way that path prediction improves control performance of ships, no application was identified until recently. Presumably, this was caused by difficulties in establishing the requirements for interfacing the predictor with the navigation systems on board ships. Current computer systems seem to have solved this problem (Heikkilä, 1993). High-precision position and movement information, being a most essential element for path prediction, may be obtained by means of existing Differential Global Positioning Systems (DGPS). Nowadays position information with a long-term accuracy is better than 2 m (Heikkilä, 1996); the same accuracy was found by Offermans, Helwig & Van Willigen (1997) who combined Global Navigation Satellite System (GNSS) with the long-range radio navigation system Loran-C.

Three different path prediction concepts are considered in the current study:

- Extrapolation of the ship’s movement, a relatively simple method of path prediction (Heikkilä, 1993). Extrapolation of the ship’s course and speed results in a speed vector; extrapolation of speed and rate of turn information provides curved predicted tracks. A disadvantage of extrapolation based prediction is its limited accuracy; current extrapolation is based on the assumption that the actual state of the vessel remains the same. In practice this is not the case.

- Fast time calculation of a fixed prediction model, based on a model that contains a set of hydrodynamic equations describing the manoeuvring characteristics of the vessel and the
effect of disturbances (uniform in time and space). The predicted track ahead may be obtained by fast-time iterative calculations of the prediction model; for each iteration the model inputs the actual state of the vessel (Inoue, Hirano, Kijima & Takashina, 1981; Stassen, 1987). Such a prediction model is specific because its parameters are fixed and have to be identified and estimated for the individual vessel; the model needs extensive tuning which decreases its reliability.

- To overcome this problem, Van Amerongen (1982) and Passenier (1989) developed path prediction based on fast time calculation of an adaptive model. This model is based on a relatively simple mathematical ship motion model (Nomoto, Taguchi, Honda & Hirano, 1957) and increased its accuracy by continuously adapting its parameters to the changing navigational conditions. They used Extended-Kalman filtering techniques to solve the combined state and parameter estimation problem.

Support of the navigation function (N) concerns support of open-loop control based on learned input/output relation. This requires information of long-term effects on the controlled variable of short-term decisions, where alternatives are presented to safely solve the problem situation (N,P). Diehl & Sterman (1995), and Kerstholt (1997) stated that human cognitive capabilities do not include the ability to solve systems of higher-order nonlinear differential equations intuitively. They concluded that because people are in general not well suited to deal with the time dimension in dynamic tasks, decision support has to show relations between context, decision process and actual choice. A technical support system for supervisory control should therefore not only present the predicted path as such — where prediction is based on a single process tuning action — it should also show the consequences of a range of process tuning actions with respect to the process reaching its safety margins for the particular situation (N,I). In the case of ship navigation, this type of predictive information represents areas of safe passage. Such information helps the navigator to better assess the probability of success for alternative routes. Selecting the safest alternative route (N,E) may then be achieved by applying basic decision rules for guidance, considering the safety margins. To keep a vessel within the safety margins is only a matter of guiding the vessel along the newly selected alternative route (G, C).

Based on this literature overview, three expectations are listed on the support of supervisory vehicle control:

- Expectation 1: preview information supports routine supervisory control (guidance function) in slow tasks, i.e., where control is performed with less than maximum control effort (G,P).
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- **Expectation 2**: preview and path prediction information support routine supervisory control (guidance function) in rapid tasks, i.e., where control is performed with near to maximum control effort (G.I).

- **Expectation 3**: preview and path prediction information, in combination with information presenting the predicted manoeuvring margins — the so-called predicted capability envelope of the controlled vehicle — support non-routine supervisory control (navigation function) (N). These predicted manoeuvring margins enable selection of the safest route to proceed; preview and path prediction information enable safe guidance and control along this selected route (G and C).

Expectation 1 confirms earlier research in this respect (Kelley, 1968; Kok & Stassen, 1980; Godthelp, 1984; Schuffel, 1986; Papenhuijzen, 1994) and is considered as a reference.

Outline of the study

In order to test these three Expectations on the effectiveness of supervisory vehicle control support systems, five experiments were carried out. For this purpose, simulator facilities were used in which participants were requested to perform specific control tasks. The experimental conditions required the execution of different supervisory control functions, while using different support systems. Task conditions of different complexity were created by generating scenarios of various complexities. After analysis of the experimental results, expectations made about operator performance could either rejected or confirmed. All experimental conditions included the use of automated systems for control function execution (C).

**Experiment 1** (Chapter 2)
Expectation 1 is tested. In a flight simulator, pilots had to perform a spatial tracking task with a fighter aircraft, a target intercept task. Considering the relatively high-frequency response capability of a fighter aircraft, task performance primarily depends on the ability of the pilot to directly perceive the desired route. High-level task performance requires accurate preview (G.P). Different qualities of preview were provided: Limited preview by a conventional plan-view radar display representation, and a full spatial preview by a perspective spherical radar display representation. Task difficulty varied with the need of control effort; approaching targets are difficult to intercept, receding targets are easy to intercept. Task performance was assessed in terms of time to intercept and tracking accuracy.
Task performance was expected to be poor in conditions where limited preview was provided. Limited preview leads to uncertainty about the route to be followed, decreasing control performance. Best task performance was expected when full spatial preview was provided.

**Experiment 2** (Chapter 3)
The experimental conditions are identical to Experiment 1, however, in order to test the statement in Expectation 1 that only accurate preview is required in high-frequency response tracking tasks (G.P), predictive information was added to the full spatial preview radar display representation. Task performance was assessed in terms of time to intercept and tracking accuracy.

Task performance was expected to maintain at the same high level, irrespective of the type of predictive information added.

**Experiment 3** (Chapter 4)
Expectation 2 is tested. In a ship manoeuvring simulator, navigators had to follow a planned route with a medium size vessel. This route consisted of a set of waypoints with course alterations. Considering the relatively low response capability of the vessel, control performance primarily depended on the ability of the navigator to directly perceive the course of the planned route. Task performance then depends on the quality of the preview (G.P), and on the ability of the navigator to anticipate short-term manoeuvres for guidance (G.I). For preview support, the planned route was presented on a navigation display. For anticipation support, either basic speed and position navigation information was available, or path prediction information based on fast time model calculations. Task difficulty varied with the need of control effort; limited course changes are easy to perform, larger course changes are difficult to perform. Task performance was assessed in terms of navigational accuracy.

Task performance using basic speed and position information was expected to be high in conditions where limited course alterations were required; these are conditions where less than maximum control effort is needed (G.P). Task performance was expected to decrease in conditions where large course alterations had to be performed and navigators need to anticipate. In these circumstances they frequently use rules-of-thumb to determine the required control actions. Because these rules are inaccurate, and because navigators are anticipating monitored information, performance was expected to decrease (G.I). Because path prediction supports anticipation at this level, task performance was expected to return at a constant high level in conditions where path prediction information was used.
Experiment 4 (Chapter 5)
The experimental conditions are more or less identical to Experiment 3, however, in order to test the statement in Expectation 2 that preview and predictive information are required in only routine task conditions, unexpected events were included in certain scenarios. In a ship manoeuvring simulator, navigators had to follow a planned route with a large vessel. Then, an unexpected passing manoeuvre had to be performed because of an obstruction in the fairway. For passing manoeuvres with small course alterations, control performance was estimated to depend primarily on the ability of the navigator to perceive the course of the fairway, requiring preview (G.P). For passing manoeuvres with large course alterations, control performance was estimated to depend primarily on the ability of the navigator to anticipate short-term manoeuvres (G.I). Task difficulty varied with the need of control effort. For preview support, a representation of the planned route was shown on a navigation display. For anticipation support, path prediction information was presented: Path prediction based on extrapolation, or path prediction based on fast time model calculations. Task performance was assessed in terms of navigational accuracy.

Task performance was expected to be high during passing manoeuvres with limited course alterations. Adequate preview is then required, which was provided by a representation of the planned route on the information display (G.P). Task performance was expected to deteriorate rapidly with increasing magnitude of the course alterations. As was discussed earlier, navigators need to know the consequences of all possible actions in non-routine task conditions. Rules-of-thumb cannot be used because corrective actions frequently comprise multiple control actions. In that case, rule-based behaviour as well as knowledge-based behaviour are required. A representation of the predicted track ahead, particularly extrapolator-based path prediction, does not provide that type of information. For example, a predicted track ahead does not indicate when counter-rudder must be given for stabilising the vessel. Navigators generally lack this knowledge. Navigation performance was therefore expected to decrease, even in conditions where path prediction information was used.

Experiment 5 (Chapter 6)
Expectation 3 is tested. In a ship manoeuvring simulator, navigators had to cross a busy traffic separation scheme with a medium size vessel. They were told to keep other vessels at a predetermined minimum safety distance. Traffic ships approached from port and from starboard side. Traffic situation initially was such that no course or speed alteration were required in following the planned route. Then, an unexpected change in the traffic situation occurred, for instance, because one of the traffic ships changed its speed, causing collision danger. Navigators can not just perform a passing manoeuvre to avoid the problem; course alterations could lead to collision risk with other traffic ships, or, course alterations could cause the ship to exceed the fairway boundaries. Therefore, alternative safe routes for
navigation must be considered and selected first (N). Considering the voyage plan, the safety regulations, traffic rules, and fairway boundaries, alternative routes must be generated (N.P), diagnosed and verified in detail (N.I) in order to select the safest and most economical alternative route for guidance (N.E). Next, task execution concerns guidance of the controlled vessel along this selected alternative route (G, C).

In the experiment, integrated predictive information was used to support the navigator in taking these steps. Capability prediction, showing the predicted manoeuvring margins of the controlled vessel with respect to fairway and traffic ships, was used to support the selection of alternative safe routes. Preview and path prediction were used to support guidance along these routes. Selecting the proper alternative route is then a matter of considering safety margins and economical criteria (N.I). Once the alternative route is selected (N.E), task execution concerns guidance and control (G, C), with preview and path prediction support. Integrated predictive information was expected to fully support the navigator's anticipation, leading to safe control behaviour.

In Chapter 7, the main conclusions of the study are summarised.
Chapter 2

Experiment 1: Aircraft guidance with preview

Abstract — In an experiment, Expectation 1 is tested: Preview information supports routine supervisory control (guidance function) in slow tasks, i.e., where control is performed with less than maximum control effort. In a flight simulator, pilots had to perform a spatial tracking task with a fighter aircraft, a target intercept task. Considering the relatively high-frequency response capability of a fighter aircraft, task performance primarily depends on the ability of the pilot to directly perceive the course of the desired route (G.P). High level task performance then mainly requires adequate preview. Different qualities of preview were provided: Limited preview by a conventional plan-view radar display representation, full spatial preview by a perspective exocentric spherical radar display representation — with outside-in or inside-out motion reference. Task difficulty varied with the need of control effort; approaching targets are difficult to intercept, receding targets are easy to intercept. Task performance was assessed in terms of time to intercept, tracking accuracy, and pilot workload.

The results indicate that pilots were able to perform the target acquisition task extremely efficient in conditions where full spatial preview was provided, irrespective of the initial target position. This was particularly the case when inside-out motion reference was used; target acquisition time was reduced by more than 40% as compared with limited preview display conditions. Expectation 1 was confirmed.

Introduction

Rapid developments in the field of aviation radar and display technology provide greater flexibility for display formatting, especially when information from different sources needs to be presented on a single display (integrated information). It is known that related information is better understood when it is presented in a single display (Goettl, Wickens &

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1 This Chapter has been published as:
Kramer; 1991; Kelley, 1968). For visual display information this can be achieved by means of computer graphics techniques, for example, by presenting information from the vertical situation display (pitch, roll, heading, and elevation indicator) and the horizontal situation display (flight path projection on a chart) in a single perspective representation (e.g., Hollister, 1986; Schwartz & Adams, 1987). The present experiment may be considered as a follow-up on these studies and focuses on the use of augmented radar display information to support guidance functions in supervisory control.

The displayed information should fit the nature of the optimal mental processing operations required to perform the task. Wickens & Andre (1990), Haskell & Wickens (1993), and Wickens & Carswell (1995) propose an interaction between the type of task performed and the type of display most suited for that task, the Proximity Compatibility Principle (PCP), that integrated tasks yield more benefit from integrated displays. Aircraft control is an integrated task since a pilot must understand and combine location and rate of change information in 3-D. Because 3-D perspective displays show the necessary information within a single spatial representation, it may thus be expected that pilot's performance benefits more from these integrated displays than from displays representing this spatial information in separate dimensions.

The graphical representation of the external world can be shown from the position of the observer, egocentric display information, or from a position somewhere in space, exocentric display information (Wickens & Prevett, 1995). An egocentric presentation shows the external world only in one direction, suited to local guidance tasks, i.e., following a planned navigational track with limited preview. Pilots perceive themselves flying through the environment as seen from an ego-referenced frame (Wickens, Liang, Prevett & Olmos, 1994). This means that the display direction, left or right, always corresponds with the control direction. Exocentric displays separate the observer's eye point and actual position, showing the external world that surrounds the observer, thus assisting with global awareness. They represent the world either in a fixed geographical coordinate system (world-referenced; e.g., north up) or with respect to one's momentary position and orientation (ego-referenced; e.g., track up or heading up).

Research using egocentric perspective displays mainly has examined the navigation accuracy during local guidance tasks (Busquets, Parrish, Williams, & Nold, 1994; Grunwald, Robertson, & Hatfield, 1980; Roscoe, 1980; Theunissen, 1994). Research using exocentric perspective displays mainly focussed on world-referenced aspects: How effective will these displays support the situation awareness of pilots in a geographical environment? Wickens et al. (1994) investigated the flight accuracy and orientation of pilots using two-dimensional (2-D) plan-view, and 3-D perspective north up, track up and heading up situation displays. Other investigations have examined pilots' perceptions of the geograph-
Experiment 1: Aircraft guidance with preview

ical environment (Aretz & Wickens, 1992) and the assessment of collision risk (Ellis & McGreevy, 1987). Results have revealed that world-referenced exocentric displays can increase pilots' geographical orientation, but can hamper pilots' tracking performance in local guidance tasks because of the required mental transformations. For example, a north up display may cause confusion in an aircraft heading south (Haskell & Wickens, 1993; Wickens et al., 1994). Note that these investigations used more or less static scenarios. Ego-referenced exocentric display information, supporting the orientation of objects in space relative to the observer's momentary position, has hardly been a topic of much research activity. However, one may suppose that knowledge about the position of surrounding objects in space is of major importance.

Other research (Ellis, Kim, Tyler, McGreevy & Stark, 1985; Barfield & Young, 1991) has addressed methods of presenting perspective information on a display, investigating factors that influence the judgment of spatial information: grid-surface density, Geometric Field Of View (GFOV), Station Point Distance (STP), and target distance. It appeared that a perspective graphical presentation of the airspace provides a more natural (ecological) and compatible representation than a conventional plan-view display (Wickens, 1992), but it was found difficult to estimate the exact position of computer-generated objects in that space. It is necessary, though, to carefully select the design parameters of the spatial information. For example, incorrect combination of GFOV and STP causes deformation of the presented image which leads to overestimation of the elevation angle (McGreevy & Ellis, 1986).

Another important factor that affects the interpretation of perspective display information is scene dynamics during motion — the relative movement of the graphical components. In this respect, Roscoe & Williges (1975) and Roscoe (1980) distinguished motion references in avionic systems: with inside-out or ego-centered motion reference, the horizon rotates according to roll and pitch whereas the aircraft symbol remains stationary; and with outside-in or earth-centered motion reference, the horizon is stationary whereas the aircraft symbol rotates. Inside-out motion reference is compatible with the motion of the environment as it is observed from the cockpit; the aircraft is the reference, and the world is rotating. In contrast, outside-in motion reference shows the movements of the aircraft in a stationary world, representing the aircraft as a dynamic element in the real world. Research concerning the graphical representation of perspective display information as well as motion reference is reported here.

The goal of the current experiment was to test the expectation that preview information supports routine supervisory control (guidance function) in slow tasks (Expectation 1). An aircraft guidance task was chosen with the following instruction: Perform a target acquisition task with a fighter aircraft, i.e., first locate a target that appears and then perform
target interception (point the aircraft’s nose toward the target as quickly as possible). For this task, it is of vital importance that pilots have correct estimations of the target’s position, and of the route to be followed toward the target. The experimental scenarios were designed such that no unexpected events occurred.

Each participating pilot initially was asked to closely follow a lead aircraft. Because an ego-referenced frame was deployed in this task, an egocentric heading-up display should have been suited to this task (Andre, Wickens, Moorman & Boschelli, 1991). The lead aircraft disappeared without warning, reappearing as a target at a predetermined distance somewhere around the pilot’s aircraft. The pilot’s task was to locate the target and to perform interception. Egocentric displays are less suitable for this task because they provide only a limited view of the airspace in the flight direction. For high-quality task performance it is essential that the pilot obtains full preview, that is, being able to fully perceive the course of the stimulus (forcing function). Exocentric displays may meet this requirement, because targets beside or even behind are shown (Stokes, Wickens & Kite, 1990). Both the display types were used in the current experiment: an egocentric heading-up display for the initial aircraft following task and an exocentric radar display for the interception task. Of the latter display, two types were investigated: a plan-view 2-D radar display, and a perspective radar display. Because perspective information may be considered as a subset of three-dimensional information (i.e., a stereoscopic image without binocular disparity), the perspective radar display is considered a 3-D display type. In the 2-D display type, radar information consisted of an augmented circular plan-view display. The display centre represented the pilot’s aircraft; a target symbol indicated the target position relative to the pilot’s aircraft. The display was augmented with colour coding for relative target position, and a separate scale for target elevation was used. In the 3-D condition, radar information consisted of an exocentric perspective spherical display, depicting the surrounding airspace as a dot pattern. The pilot’s aircraft was again presented in the display centre with the target symbol on the sphere indicating the target position relative to the pilot’s aircraft. Radar information was normalized, that is, the entire airspace surrounding the aircraft, including the targets, was depicted on the sphere. The viewpoint was slaved to move with the aircraft. To investigate the effect of target flight direction on task performance, conditions were created in which the target was, either approaching, or flying away from the pilot’s aircraft.

It was predicted that the target acquisition and interception task would be performed faster and easier with a perspective radar display. First, this was predicted by the PCP: Target azimuth and elevation, both closely related task variables, were integrated in a single display. Second, a perspective display provides full preview by depicting the entire airspace surrounding the aircraft. Perspective display information with inside-out motion reference would support the acquisition task better than perspective display information with out-
side-in motion reference: Inside-out motion reference provides maximum compatibility with the apparent motion of the outside world. Only in that case, no effect of initial target position on task performance was expected. Outside-in motion reference may deteriorate task performance because of possible inversion of the control direction.

Pilot's performance was analysed and evaluated in terms of target acquisition time, tracking performance and mental workload. Because mental workload is influenced by many factors, there is no single measure sensitive to all aspects of mental workload. Therefore, a combination of different techniques was applied. Workload was determined by using subjective rating techniques and by investigating the pilot's physiological reactions to normal and high-workload conditions. In most workload studies, physiological workload measures were obtained over work periods of at least several minutes (Veltman, 1991). In the current experiment, the duration of the high-workload trials was one minute, enabling the evaluation of the pilot's workload at a microlevel with high resolution. Details of the analyses are discussed below.

Method

Participants
Ten men and one woman participated in the experiment. Five were experienced helicopter pilots, two were aspirant pilots, and four were navigators with experience in helicopter flying. Their ages ranged from 24 to 32 years.

Target acquisition task
Participating pilots, flying the intercepting-aircraft, were initially required to follow a lead aircraft at a 1,500 ft distance with a speed of 500 knots, at 15,000 ft altitude. The lead aircraft was clearly visible so that changes in distance and course could be easily perceived. This aircraft continued in a straight course or started a horizontal curve (turn rate 5°/s). Then, after 8, 12 or 16 s, the lead aircraft suddenly disappeared and reappeared as a target somewhere on an imaginary sphere around the intercepting-aircraft at a 10,000 ft distance. The participants were instructed to intercept the target within the shortest possible time by pointing the nose of the intercepting-aircraft as accurately as possible toward the target as soon as it reappeared. The trial terminated after target lock-on was achieved, i.e., the pilots succeeded in keeping the target for at least 2 s within 10 degrees of the intercepting-aircraft's heading. Otherwise, the trial ended after 90 s. Actual performance measurement started at the moment of target reappearance. At the end of each trial, the participants were requested to indicate their subjective effort on a rating scale.
The speed of the target aircraft was 500 knots, in a direction either away from the center of the imaginary sphere or toward the centre of that sphere. The first situation was called an easy trial because the target aircraft was receding and would be relatively easy to approach from behind; the second situation was called a difficult trial because the target was approaching the intercepting-aircraft and would pass close by after a few seconds. The flight direction of the target remained unchanged, unless the target arrived at zero altitude, in which the target would continue its flight along the earth’s surface. Trials were presented in blocks of 38. Each block consisted of 18 easy trials and 18 difficult trials, presented in randomized order. Each group of 18 trials had different target positions: 6 trials with the target initially above, 6 at level with, and 6 with lower than the intercepting-aircraft position. These trials were considered normal workload trials. In addition, two high-workload trials were included in each block. During these trials, the target aircraft was following curved trajectories while constantly seeking the participant’s intercepting-aircraft, with a speed of 900 knots. This made the target interception task difficult to perform. In addition, a so-called Continuous Memory Task (CMT) had to be performed as a secondary task, consisting of a letter-detection task presented by headphones, one letter each 1.5 s. The participants were required to press a button each time they recognized one of four target letters. In addition, the number of target letters had to be counted in separate tallies. The button had to be pressed twice each time a target letter was repeated.

Apparatus
The experiment was carried out in the TNO Human Factors Research Institute (TNO-HFRI) fixed-base flight simulator. This simulator consists of three elements: a video image generator with projection system, a mock-up of an instrumented cockpit, and computer systems with an aerodynamic model of the aircraft.

A three-channel Evans and Sutherland ESIG2000 high-speed graphics processor was used to generate synthetic exterior cockpit scenes. This processor generated multiple-channel high-resolution video images (1500–2000 textured polygons and 800×600 pixel resolution per channel). The image update frequency was 30 Hz. For three channels, the total viewing angle was 156° horizontal and 42° vertical. The images were presented on a spherical dome by means of a Seos PRODAS HiView S-600 projection system. In the centre of the dome, a mock-up of the cockpit was installed. The observation distance was about 3 m.

The generic fighter aircraft cockpit mock-up was partially instrumented with displays and controls (Figure 2.1). In addition to the force stick and throttle used for aircraft control, a three-position slide was installed to enable speed brake control (0°, 30°, and 60°). System information (altitude, airspeed, heading, vertical speed, and speed brake status) was presented on the main display; information concerning roll and pitch attitude,
climb speed, and flight direction was presented in a Head-Up Display (HUD), projected on the dome in front of the participants. The main display depicted a perspective synthetic grid surface, representing geographical and tactical information as well as a cross symbol, indicating the target position. The cross symbol was only visible within 10° of the intercepting-aircraft’s flight direction. In the lower left part of the main display, the investigated radar display types were presented. A schematic representation of the main display is shown in Figure 2.2.

![Image of cockpit mock-up and projected scene](image)

**Figure 2.1** Overview of the cockpit mock-up and the projected scene in the flight simulator.

The aerodynamic model of the aircraft was based on a six-degrees-of-freedom model of a F-16 fighter (Schuring, 1983). This model was validated in full-scale trials (Van der Geest, 1985). Time constant of aircraft motion in roll and pitch were 0.6 s and 2.0 s, respectively. Physiological data were recorded on a CODAS digital recording system (DATAQ Instruments, Akron OH, USA; release level 5).
Figure 2.2 The main display. The earth is represented by a grid, the target by an \( \times \) symbol, the flight direction by a \( + \) symbol, and the length axis of the intercepting-aircraft by an \( \star \) symbol. Additional indicators for airspeed, vertical speed, altitude, and heading are shown. The radar display is presented in the lower left, in this case a two-dimensional plan-view radar image with an additional target elevation indicator.

Displays

Three radar display types were investigated (Figure 2.3):

(i) 2-D: target position was shown in a plan-view radar image in combination with a target elevation indicator;

(ii) 3-D outside-in: target position was shown in a perspective exocentric sphere with outside-in motion reference and an additional target distance indicator;

(iii) 3-D inside-out: target position was shown in a perspective exocentric sphere with inside-out motion reference and an additional target distance indicator.
Figure 2.3 Overview of the investigated display types. The left figure shows a two-dimensional (2-D) radar display with a separate target elevation indicator; the right figure shows a 3-D radar display with a separate target distance indicator. The intercepting-aircraft symbol is always presented in the display centre. Horizon and wing plane are presented as indicated. The line ahead, perpendicular to the wing plane, is the visor. Two 3-D configurations were investigated: outside-in motion reference (the sphere with horizon and target symbol remain horizontal, whereas the intercepting-aircraft symbol rotates as a function of pitch and roll) and inside-out motion reference (the intercepting-aircraft symbol with wing plane remains horizontal, whereas the sphere with horizon and target symbol rotates as a function of pitch and roll). This figure shows a 3-D radar display with outside-in motion reference.

The 2-D display type consisted of a conventional circular radar display with the participant's intercepting-aircraft position in the centre, orientation heading up (Figure 2.3a). Position and speed of the target aircraft were represented by a symbol with speed vector. The colour of the symbol indicated the relative target position: blue if the target was flying at the same or at higher altitude and pink if the target was flying lower than the intercepting-aircraft. An additional scale indicated target elevation.

The 3-D display type showed the radar display as a perspective spherical picture (Figure 2.3b). Half the sphere was coloured blue, representing the airspace above the horizon, the other half was brown, representing the (air)space below the horizon. In between was the horizon (blue ring). The intercepting-aircraft symbol was presented in the display centre. Motion reference was outside-in, that is, the sphere with target symbol and horizon remained stationary (horizontal), whereas the intercepting-aircraft symbol rotated as a function of pitch and roll. The intercepting-aircraft symbol was coloured green, so was the wing plane (green ring). The viewing direction was heading up. The target aircraft was a
perspective aircraft symbol, the aspect indicating the relative flight direction. An additional scale indicated the target distance. The 3-D inside-out configuration showed radar information similar to the 3-D outside-in configuration but with inside-out motion reference, that is, the intercepting-aircraft symbol with wing plane remained stationary (horizontal), whereas the sphere with horizon and target symbol rotated as a function of pitch and roll. The viewing direction was heading up.

Performance measurement
The state variables of position, roll, pitch, heading, and speed of the intercepting-aircraft and the target were sampled and stored with an interval of 0.25 s. Performance was recorded on target acquisition time and roll-angle error. The target acquisition time was defined as the time interval between target reappearance and target lock-on, expressed in seconds. The roll-angle error was defined as the root-mean-square deviation between the actual roll-angle and the optimal roll-angle, that is, the roll-angle during which the target is positioned right above the vertical body axis of the intercepting-aircraft. The roll-angle error was expressed in degrees.

Subjective measures
Subjective effort was assessed by the Rating Scale for Mental Effort (RSME; Zijlstra, 1993). This rating scale registers mental effort as estimated by the participants and ranges from 0 to 150, with nine descriptive indicators along the axis, e.g., 2 = helemaal niet inspannend (no effort), 26 = een beetje inspannend (a bit of effort), 57 = tamelijk inspannend (rather effort), and 114 = onzettend inspannend (extreme effort). Veltman & Gaillard (1993) concluded that the RSME is a sensitive measure to changes in task load, and is even more sensitive than the National Aeronautics and Space Administration’s Task Load Index (Hart & Staveland, 1988). The RSME was also successfully used by Wei (1997).

Physiological measures
Physiological measures were recorded both during task performance and during periods of rest before and after each task block. Electrocardiograms, respiration, blood pressure, and electro-oculograms were digitally recorded. The sample rate was 100 Hz for all channels. A ten-minute period of rest, in which the participants remained seated in the simulator, was given before and after each task block. This rest period was considered the baseline condition.

Heart period. R-peaks in the electrocardiograms were detected. The heart period was defined as the average time between two successive R-peaks.
Experiment 1: Aircraft guidance with preview

**Blood pressure.** Blood pressure was measured with the TNO Finapres tonometer. A cuff around each participant's left middle finger registered systolic and diastolic blood pressure from beat to beat. Only results of systolic blood pressure are presented here.

**Respiration.** Respiration was measured by recording resistance changes due to expansion of two belts fixed around the chest and the abdomen of each participant. Both the signals were combined for peak detection. The cycle time was defined as the time interval between two successive peaks.

**Eyeblink.** Eyeblinks were derived from the electro-oculograms, measured with electrodes above and below each participant's left eye. Several parameters were extracted, two of which are reported here: eyeblink frequency and closure time. Blink frequency was defined as the number of blinks per minute and closure time was the length of time to perform eye closure. Because the duration of the trials differed for each radar display type, the blink parameters were calculated over the first 20 s. Trials lasting less than 20 s were excluded from the eyeblink analysis.

**Procedure**

Participants came in pairs for two consecutive days. On the 1st day, they had to perform practice trials with the three display types under close supervision of the experimenter. The session consisted of two blocks of 18 practice trials for each display type. On the basis of pilot studies, it was determined that this amount of trials was sufficient to obtain a stable performance level from each participant. The next day, experimental trials were performed: a block of 38 trials for each display condition.

**Analyses**

In the underlying studies, a number of statistical analyses is used. An analysis of variance (ANOVA) enables testing for significant differences between the means of various sets of measurements on the same experimental variable, where each set is obtained under its own set of conditions. A post-hoc Newman-Keuls test and a post-hoc Tukey test enable the determination which variables are contributing to the overall significance, i.e., the probability for each pair of means to differ. The Tukey test is usually more conservative than the Newman-Keuls test. For testing the significance of the relationship between categorical variables, Pearson's Chi-square test is used.
Results

Performance measurement

Target acquisition time. All participants were able to perform the target acquisition task within 90 s. A repeated measures analysis of variance (ANOVA) on the target acquisition time, with display type (2-D, 3-D outside-in, or 3-D inside-out), initial position (above, level, or lower) and trial difficulty (easy, or difficult trials) as independent variables, showed a main effect of display type [$F(2,20)=82.8; p < .0001$; explained variance 15.8%], initial position [$F(2,20)=23.7; p < .0001$; explained variance 1.9%], and trial difficulty [$F(1,10)=339.6; p < .0001$; explained variance 18.1%].

The main effect of display type revealed that participants took considerably longer to perform the task with the 2-D display than with either of the 3-D displays. The best performance was achieved with the 3-D inside-out display; the acquisition time was reduced by more than 40% as compared with the 2-D display type. A post-hoc Tukey comparison test showed all three display conditions to be significantly different ($p < .01$).

<table>
<thead>
<tr>
<th>display type</th>
<th>target acquisition time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-D</td>
<td>above, level, below</td>
</tr>
<tr>
<td>3-D outside-in</td>
<td>20</td>
</tr>
<tr>
<td>3-D inside-Out</td>
<td>10, 20</td>
</tr>
</tbody>
</table>

Figure 2.4 Target acquisition time as a function of two dimensional (2-D) and three dimensional (3-D) display type and initial position of the target aircraft, averaged across participants.
Experiment 1: Aircraft guidance with preview

The effect of initial position on task performance is illustrated in Figure 2.4, in which the mean acquisition time is presented as function of the display type and the initial position of the target aircraft. Shortest acquisition times were achieved when the target was initially located at level, i.e., at the same altitude. An interaction was found between display type and initial position of the target, $F(4,40)=12.7; p<.0001$; explained variance 0.9%. The effect of initial position on target acquisition time was large when the 2-D display was used; no effect was found in conditions with the 3-D inside-out display.

The ANOVA results concerning trial difficulty were obvious: The task was performed best during the easy trials. No interaction was found between display type and trial difficulty: there was a constant difference of about 10 s between easy and difficult trials. The longest acquisition times were measured using the 2-D display configuration, and the shortest with the 3-D inside-out display configuration. The results suggest that the difference in task execution between easy and difficult trials was approximately constant for all display types. Apparently, the pilots were unable to directly intercept an approaching target. They had to spend approximately 10 additional seconds to perform a 180 degree turn to approach the tail of the target.

Roll-angle error. An ANOVA on the roll-angle error, with display type (2-D, 3-D outside-in, or 3-D inside-out), initial position (above, level, or lower) and trial difficulty (easy, or difficult) as independent variables, showed a main effect of display type [$F(2,20)=72.1; p<.0001$; explained variance 11.6%] and initial position [$F(2,20)=16.2; p<.001$; explained variance 4.0%].

The effect of display type on roll-angle error was similar to the effect of display type on target acquisition time. Roll-angle error was considerably greater with the 2-D display than with either of the 3-D display types similar to the way display type affected target acquisition time. The best tracking performance was achieved with the 3-D inside-out display. A post-hoc Tukey comparison test showed that these results were significantly different for all display types ($p<.01$).

A significant interaction was found between display type and initial position, $F(4,40)=9.3; p<.0001$; explained variance 0.9%. In Figure 2.5, it can be seen that there was a large effect of initial position on roll-angle error for the 2-D display type: A post-hoc Tukey comparison test showed that the roll-angle error increased significantly when the target aircraft was initially positioned below or above the intercepting-aircraft ($p<.001$). This effect was also significant for the 3-D outside-in display type ($p<.001$); no differences were found for the 3-D inside-out display type.

The effect of trial difficulty on roll-angle error was evident: The best tracking performance was obtained during the easy trials. Again, no significant interaction was found between display type and trial difficulty, $F(2,20)=3.4; p=.05$. 

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Figure 2.5 Roll-angle error as a function of two dimensional (2-D) and three dimensional (3-D) display type and initial position of the target aircraft, averaged across participants.

Subjective measures
An ANOVA on the RSME scores, with display type (2-D, 3-D outside-in, or 3-D inside-out), initial position (above, level, or lower) and trial difficulty (easy, or difficult) as independent variables, showed a main effect of display type \( F(2,20)=16.8; p<.0001; \) explained variance \( 8.6\% \), initial position \( F(2,20)=62.6; p<.0001; \) explained variance \( 2.3\% \), and trial difficulty \( F(1,10)=127.5; p<.0001; \) explained variance \( 2.8\% \).

The effect of display type on the workload score corresponded closely with the effect of display type on target acquisition time. The pilots felt less effort when they used either of the 3-D displays instead of the 2-D display. In particular, the 3-D inside-out display was felt to cause minimum effort, \( F(2,20)=16.8; p<.001 \).

A significant interaction was found between display type and initial position, \( F(4,40)=4.8; p<.01; \) explained variance \( 0.2\% \). Trials with initial target position at level showed less subjective effort than trials with initial target position below or above
Experiment 1: Aircraft guidance with preview

(Figure 2.6). A post-hoc Tukey comparison test showed that only in the 3-D inside-out display condition RSME ratings were not significantly different ($p < .01$).

The effect of trial difficulty on RSME scores was obvious. Difficult trials always resulted in higher mental-workload scores, irrespective the display type.

![Workload Score Chart](image)

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**Figure 2.6** Subjective workload score as a function of two dimensional (2-D) and three dimensional (3-D) display type and initial position of the target aircraft, averaged across participants.

For a comparison between normal workload and high-workload task performance, only trials with a corresponding initial position to the target aircraft were considered. The results are presented in Table 2.1. The participants needed more time for target acquisition and the RSME workload scores were higher during high-workload task conditions, $F(1,10)=13.7; p < .01$, and $F(1,10)=38.1; p < .001$, respectively. The RSME scores for the 2-D display under normal workload task conditions were almost identical to the RSME scores for the 3-D inside out display under high-workload task conditions. The target acquisition time with the 2-D display was strongly impaired by high-workload task conditions as compared with both the 3-D displays, particularly when considering the 3-D inside out display; an interaction was found between display type and workload task condition,
Chapter 2

$F(2,20)=3.6; p < .05$. The RSME scores showed the opposite pattern; the difference in RSME ratings between normal and high-workload task conditions was smaller with the 2-D display than with the 3-D displays, $F(2,20)=4.4; p < .05$.

<table>
<thead>
<tr>
<th>Measure</th>
<th>2-D</th>
<th>3-D outside-in</th>
<th>3-D inside-out</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal</td>
<td>High</td>
<td>Normal</td>
</tr>
<tr>
<td>Target acquisition time (s)</td>
<td>25.9</td>
<td>45.0</td>
<td>18.0</td>
</tr>
<tr>
<td>RSME workload score</td>
<td>64.2</td>
<td>87.7</td>
<td>48.1</td>
</tr>
</tbody>
</table>

Note: 2-D = two-dimensional; RSME = Rating Scale for Mental Effort

**Physiological measures**

A summary of the results is presented in Table 2.2. An ANOVA on the physiological measures, with display type (2-D, 3-D outside-in, or 3-D inside-out) and workload task condition (rest, normal, or high) as independent variables, indicated that for the heart period, blood pressure, and the cycle time, no significant differences were found between the three radar display conditions, or between the easy and difficult trials. The heart period was higher during the periods of rest than during task execution [$F(1,10)=40.5, p < .001$] and heart period was higher during normal workload conditions than during high workload conditions [$F(1,10)=20.7; p < .001$]. Blood pressure was lower during the periods of rest than during task execution [$F(1,10)=8.56; p < .05$], and blood pressure was lower during the normal workload conditions than during high-workload conditions [$F(1,10)=18.8; p < .001$]. Participants breathed faster during task execution (shorter cycle time) than during periods of rest, $F(1,10)=28.1; p < .001$. No significant difference in cycle time was found between normal and high workload conditions.

Blink frequency and closure time showed differences between the display conditions, $F(2,20)=9.5; p < .01$ and $F(2,20)=11.7; p < .001$, respectively. Blink frequency and closure time were higher with the 2-D display than with the 3-D displays. No significant difference between the two 3-D display conditions was found. More eyeblinks were made during the periods of rest than during task execution [$F(1,10)=20.7; p < .01$], whereas closure time during periods of rest was longer than during task execution [$F(1,10)=48.6; p < .001$]. No significant difference between the normal and high-workload conditions was found.
Table 2.2 Results of the physiological measures for the periods of rest and for the normal and high workload task conditions.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Rest</th>
<th>2-D Normal</th>
<th>2-D High</th>
<th>3-D outside-in Normal</th>
<th>3-D outside-in High</th>
<th>3-D inside-out Normal</th>
<th>3-D inside-out High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart period (ms)</td>
<td>831</td>
<td>782</td>
<td>733</td>
<td>810</td>
<td>752</td>
<td>791</td>
<td>717</td>
</tr>
<tr>
<td>Blood pressure (mmHg)</td>
<td>133</td>
<td>146</td>
<td>150</td>
<td>144</td>
<td>148</td>
<td>144</td>
<td>147</td>
</tr>
<tr>
<td>Respiratory cycle time (s)</td>
<td>4.4</td>
<td>3.8</td>
<td>3.7</td>
<td>3.8</td>
<td>3.5</td>
<td>3.8</td>
<td>3.5</td>
</tr>
<tr>
<td>Blink frequency (Hz)</td>
<td>17.9</td>
<td>13.7</td>
<td>17.8</td>
<td>5.5</td>
<td>7.6</td>
<td>5.3</td>
<td>10.4</td>
</tr>
<tr>
<td>Blink closure time (s)</td>
<td>116</td>
<td>102</td>
<td>102</td>
<td>97</td>
<td>93</td>
<td>91</td>
<td>86</td>
</tr>
</tbody>
</table>

Note: 2-D = two-dimensional

Discussion

The potential benefits of perspective displays for situation awareness support were demonstrated in this study by using a target acquisition task. A considerable reduction in the target acquisition time was obtained when pilots used a perspective radar display instead of a conventional plan-view display in the cockpit. This finding confirms one of the most important benefits of 3-D perspective display representation as was observed by Wickens et al. (1994): The elimination of the time-consuming scanning that is necessary to go back and forth between the several parts of a display. In the 2-D display, a circular radar image indicating target azimuth and a separate linear indicator for the target elevation had to be scanned and mentally combined for target position estimation. In both the 3-D perspective displays, target azimuth and elevation were presented in a single object. The results also underline the PCP, the principle that relates the processing of displayed information to the task characteristics (Haskell & Wickens, 1993): Tasks in which close mental proximity is required (i.e., information integration) are best served by proximate displays, whereas tasks that require low mental proximity (i.e., independent processing of two or more variables) benefit from more separate displays. In the 3-D perspective sphere, both the target elevation and target azimuth were integrated. For target acquisition, these variables represent information of close mental proximity.

Maximum tracking performance could be achieved only when the correct roll angle was immediately selected. Analysis of the roll-angle error data indicated, however, that the pilots did not have that strategy with the conventional plan-view display, nor with the perspective outside-in motion referenced display. The greater roll-angle errors with these display types could be a result of inaccurate roll-angle selection, however, observations of
the experimenter and self-observations of the pilots made clear that a more or less sequential tracking strategy was followed: First, the horizon was followed until the correct heading angle was obtained; then, the pitch was controlled toward the required target elevation angle. This two-step approach was not as effective and resulted in longer acquisition times. The content of an inside-out motion-referenced display is compatible with the motion of the external world that does not require mental transformation for the interpretation of the radar image. This made the pilots instantaneously select the correct roll angle. The tracking task was then only a matter of pulling up the nose of the intercepting-aircraft, simplifying the task and reducing the roll-angle error to a minimum.

Inside-out motion reference provided a direct relationship between the displayed movement of the scene and the perceived movements of surrounding objects. The display elements representing the outside world — three in this case — the sphere (globe) of the perspective radar display, the displayed horizon in the main (local guidance) display, and the visual horizon as seen from the cockpit, were consistent in this display, making the presented information ecologically valid (Andre et al., 1991; Wickens, 1992). The tracking task could therefore be considered as a natural process. The perspective sphere was presented by a dot pattern, providing adequate preview for tracking (Poulton, 1974). As was observed by Wickens and Prevett (1995), 3-D displays can be used very efficiently for local guidance tasks: in the current experiment the target acquisition time was reduced by more than 40%. It is obvious that this is a major improvement in performance. It is therefore concluded that the exocentric perspective display with inside-out motion reference, as was used in this experiment, provided adequate spatial awareness support and allowed proper anticipation, which resulted in an optimum tracking strategy. Note that this is valid only in combination with the main display used in this experiment and does not refer to the individual radar displays.

In the current experiment, a constant difference was found in task performance across all three displays between easy and difficult trials, that is, whether the target was initially receding or approaching. This difference was caused by the time taken by first turning toward the approaching target and then performing a full turn manoeuvre after the target had passed during difficult trials. Performance increase could be obtained by starting the full turn manoeuvre at an earlier moment. Therefore, it may be useful to add predictive information about the target’s flight behaviour to the current perspective display. This needs further investigation.

The subjective effort scores showed almost the same pattern as the performance data. The pilots felt that less effort was needed when perspective displays were used; in particular, they felt more comfortable with the inside-out motion display. However, subjective ratings are only one aspect of the overall workload (Hart & Staveland, 1988). The participants had
to rate only the effort expended, not mentioning other aspects of the task. In its current form, it is questionable whether they were able to do so (O’Donnell & Eggemeier, 1986). The ratings were probably influenced by other aspects of workload, e.g., satisfaction with their performance. So, it cannot be concluded that the 2-D display forced higher mental effort, as would be concluded by considering the RSME scores alone.

Participants have to expend more energy when the task requires mental effort (Gaillard & Wientjes, 1994), which can be measured with cardiovascular measures. Results of the physiological measures in the current experiment revealed that heart period, blood pressure, and cycle time did not differ between the three radar display conditions, indicating that the physiological effort did not differ. Only when the CMT had to be performed in combination with the acquisition task, changes were found in the cardiovascular measures, indicating an increase in mental effort during the high-workload conditions. The RSME ratings showed differences between the radar displays and between the normal and high-workload trials: The scores for the normal trials with the 2-D display were almost identical to the scores for high workload trials with the 3-D display.

Differences in performance on tasks may be due to data-limited or resource-limited characteristics of the individual task (Norman & Bobrov, 1975). Performance on a data-limited task is limited by the amount of the information available. Putting forth more effort in this kind of task will not improve performance. Performance on a resource-limited task depends on the available mental resources of the operator. Investing more effort improves performance. It seems that the differences among the radar displays in the current experiment were of a data-limited nature, because no differences in cardiovascular reactions were found between the display types. The differences between the normal and high-workload conditions were due to the resource-limited nature of the CMT secondary task and the dual-task situation as such. In general, participants are not very well able to differentiate between different aspects of mental workload (see O’Donnell & Eggemeier, 1986). By asking participants to rate their mental effort, they are likely to include other aspects of workload. In the present experiment, it seemed that the participants included both mental effort and performance satisfaction. Thus, subjective ratings provided global information about workload; the physiological measures were sensitive to mental effort only.

The eyeblink data showed that the participants made fewer eyeblinks during task execution than during periods of rest. Furthermore, eyeblinks were made faster during task execution. During information intake, participants need to minimize the loss of information due to eye closure. Low blink frequencies were found during visually demanding tasks—tasks requiring a considerable amount of visual attention (Stern, Boyer & Schroeder, 1994). In the present study, more eyeblinks with a longer closure time were made when the 2-D display was used as compared with the 3-D displays. This result is contradictory because the 2-D display is not likely to be less visually demanding than the 3-D displays. Partici-
pants were expected to perform the same or show more eyeblinks, when 3-D displays were used. Further analysis revealed that far more vertical eye movements were made with the 2-D display than with the 3-D displays. The target elevation presented with the 2-D radar had to be matched with the intercepting-aircraft pitch attitude, presented in the HUD. To verify this, participants frequently changed eye position from radar to HUD. Most eyeblinks were then made. So, participants did not blink more frequently because the 2-D display was less visually demanding but because they made more vertical eye movements. This finding shows that vertical eye movements should be taken into account when one is interpreting eyeblink data. Furthermore, participants seem to blink very efficiently: They tend to blink during eye movements when they cannot take in visual information.

Conclusion

The results of the experiment show that preview information effectively supports supervisory control in the (routine) guidance function, when slow tasks are performed. Expectation 1 was confirmed. Performance was poor in conditions with limited preview (with a plan-view display type), performance was high in conditions with full preview (with a spherical perspective display type).
Chapter 3

Experiment 2: Aircraft guidance with preview and path prediction\(^2\)

Abstract — In an experiment, Expectation 1 was tested in the same guidance task of Experiment 1, however, additional path prediction information was presented to the pilot. Participating pilots were provided with the most effective display type of Experiment 1 (a perspective exocentric radar display with inside-out motion reference), with or without additional predictive information on the target's future track ahead. Task performance was measured in terms of target acquisition time, tracking accuracy, and subjective workload.

Results of the experiment show that task performance was not affected when prediction information was presented; the results even suggest a tendency in performance decrease. This confirms Expectation 1.

Introduction

The goal of this study was to investigate whether additional path prediction information affects task performance in situations described in Expectation 1. Therefore, basic the same conditions were used of Experiment 1, however, additional path prediction information was presented on the perspective radar display indicating the future track ahead of the target. Since it was remarked that an (inside-out motion reference) perspective display information provided adequate preview, one could imagine that anticipation support based on path prediction could further increase pilot task performance.

Two additional prediction display types were investigated (Figure 2.7):

(i) speed-course-extrapolator. Path prediction was based on linear extrapolation of the relative displacement of the target aircraft, with the assumption that flight behaviour of participant's aircraft and target aircraft remain the same;

(ii) speed-course-pitch-extrapolator. Prediction type (i) was supplemented with linear extrapolation of the participant's aircraft pitch rate. This variable was supposed to mainly affect the tracking speed because target interception is mainly a matter of

\(^2\) Adapted from:
pulling up the nose of the aircraft; roll attitude only affects tracking direction. Because changing the roll attitude concerns a process with a small time constant, this was not included in the prediction. In a pilot session previous to the experimental trials, the optimal prediction time was determined at 10 s. This appeared to be the time to perform a full turn around manoeuvre. Prediction time less that 10 s did not seem to contribute in the perception of a target approach; prediction time greater than 10 s caused too early reactions of the pilot which could lead to manoeuvres in which the participant’s aircraft appeared ahead of the approaching target, which should be avoided.

Pilots were asked to perform the same target acquisition task of Experiment 1: Control a fighter aircraft and perform a target acquisition task. In the cockpit, the same integrated main display was used, with HUD information projected in front of the pilot. Three display configurations were investigated: the 3-D inside-out radar display without prediction as reference condition, supplemented with either the speed-course-extrapolator, or with the speed-course-pitch-extrapolator. Pilot performance was determined in terms of target acquisition time, tracking performance and subjective mental workload.

Task performance was expected to be identical to the performance of Experiment 1, even in situations where the target approached the participant’s aircraft.

Method

Participants
Seven male and one female participated in the experiment. Seven of them were experienced helicopter pilot, one was observer-navigator. Their ages ranged from 23 to 31 years.

Task
The participants were asked to perform the task that was used in Experiment 1: initially follow a lead aircraft that suddenly disappears and reappears as a 10,000 ft distant target. The participants first had to locate the target and to perform an interception manoeuvre (i.e., point the aircraft’s nose toward the target as quickly as possible), until lock-on was established (i.e., keep the target at least 2 s within 5° bearing). Targets were either receding (easy trials), or approaching (difficult trials).

By the end of each trial, participants were requested to indicate their subjective effort on a rating scale. Trials were performed in blocks of 36, each block consisting of 18 easy and 18 difficult trials in random order. Each group of 18 had different target positions:
Experiment 2: Aircraft guidance with preview and path prediction

6 trials with the target initially above the participant's aircraft position, 6 at level, and 6 lower than the participant's aircraft position.

**Apparatus**
The experiment was carried out in the flight simulator of Experiment 1.

**Displays**
The investigated radar display types (Figure 3.1) were based on the 3-D perspective display type with inside-out motion reference, being the display type that resulted in the best pilot task performance in Experiment 1, here referred to as the standard perspective display type:

(i) *no prediction*: relative target position was presented in the standard perspective display type. This was considered the reference condition;

(ii) *speed-course-extrapolator*: display type (i) was supplemented with a solid line, representing the predicted track ahead (radial displacement) of the target, determined by extrapolation of its relative speed vector. Predicted information was only presented in case the calculated radial displacement of the target was at least 60 degrees;

(iii) *speed-course-pitch-extrapolator*: display type (ii) was supplemented with a tracking indicator: a circle representing the predicted flight direction of the participant's aircraft.

![Figure 3.1 The investigated display types: (a) no prediction, the standard perspective display type; (b) speed-course-extrapolator; and (c) speed-course-pitch-extrapolator. The open circle represents the predicted flight direction of the controlled aircraft, the solid circles represent the predicted flight path of the target aircraft.](image-url)
Chapter 3

Performance measures
Performance measures were identical to Experiment 1, i.e., target acquisition time, roll-angle error and RSME subjective workload.

Procedure
Participants came in pairs. During the morning session, practice trials were performed with the different display configurations. Each practice session consisted of two blocks of 20 trials for each display type. Pilot sessions had indicated that this was sufficient to obtain a constant level of performance. Because it is not possible to obtain a full balanced experimental design with eight participants, it was decided that four participants performed their practice trials with the display types in the order (i), (ii), (iii) and four participants in the order (iii), (ii), (i); the same order in which the experimental trials were presented in the afternoon.

Results

Results of an analysis of variance (ANOVA) on target acquisition time, roll-angle error and mental workload scores, with display type (no prediction, speed-course-extrapolator, or speed-course-pitch-extrapolator) and trial difficulty (easy, difficult) as independent variables, showed a main effect of trial difficulty on acquisition time and mental workload, $F(1,7)=442.0; p < .001$ and $F(1,7)=30.0; p < .001$, respectively. Both the variables were in average highest in the difficult trials. The difference in target acquisition time between easy and difficult trials was the same for all display types (i.e., 10 s). No effect of display type on roll-angle error and workload score was found.

Discussion

The potential benefits of predictive information was investigated as an addition to Expectation 1, i.e., the statement that preview supports guidance task in situations of sufficient response of a system, using the same target interception task of Experiment 1. Prediction information was added to the best display representation of Experiment 1; the perspective inside-out radar display. The results revealed that performance was not affected when prediction information was added. The results even suggested a tendency in performance decrease. Identical results were found for the mental effort scores. The perspective inside-out radar display of Experiment 1 provided adequate preview and allowed proper anticipa-
Experiment 2: Aircraft guidance with preview and path prediction

tion, leading to optimal task performance. Additional prediction information did not improve pilot’s interpretation of the displayed information; it definitely increased the display complexity in terms of presented elements. This phenomenon is known as display clutter (Stokes et al., 1990; Korteling & Van der Borg, 1995).

Conclusion

No performance increase was found when prediction information was added to preview information in order to support guidance in slow tasks. This confirms the findings of Experiment 1.
Chapter 4

Experiment 3: Ship guidance with preview and path prediction

Abstract — In an experiment, Expectation 2 was tested: Preview and path prediction information support routine supervisory control (guidance function) in rapid tasks, i.e., where control is performed with near to maximum control effort. In a ship manoeuvring simulator, participants were required to guide a medium size vessel in open sea along a planned route. Considering the relatively low response capability of the ship, control performance depends primarily on the ability of the navigator to directly perceive the course of the planned route. Task performance then depends on the quality of the preview (G.P), and on the ability of the navigator to anticipate short-term manoeuvres for guidance (G.I). For preview support, the planned route was presented on a navigation display. For anticipation support, either basic speed and position navigation information was available, or path prediction information based on fast time model calculations. There was no wind or current. Task difficulty varied with the need of control effort; limited course changes are easy to perform, large course changes are difficult to perform. Navigational performance was assessed in terms of tracking accuracy.

Results of the experiment show that accurate control was achieved when preview as well as path prediction information were provided; navigational performance remained at a high level, even when task difficulty increased. Navigational performance decreased by a factor of three when only preview information was provided, i.e., with existing navigation methods based on basic speed and position information. Expectation 2 was confirmed.

Introduction

The goal of the current study was to investigate the expectation that combined preview and path prediction information support routine supervisory control tasks (guidance tasks) in

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3 Adapted from:
situations of insufficient response capability of the system (Expectation 2). Ship control is such a task situation, where the navigator tries to follow a planned route; the response capability of the ship system is relatively low in situations of large course alterations, and relatively high in situations of limited course alterations.

In a ship manoeuvring simulator, participants were instructed to follow a planned route with a medium size vessel (30,000 dwt). There was no wind or current, and no unexpected events occurred (guidance task). Each route was composed of route segments with five different course changes. Navigation information was presented on an integrated navigation display: A representation of the planned route and radar information providing preview, and additional information to support anticipation: Path prediction, or conventional speed and position information, i.e., a ground velocity vector (ship's true vector; Sheridan, 1966), or parallel-indexing (Spaans, 1979).

With path prediction, the planned route and the predicted track ahead for a pre-selected new course were shown. In the approach to a waypoint there was ample time for navigators to judge the predicted track ahead with respect to the planned route. At the moment that the predicted track ahead corresponded with the planned route, the course change manoeuvre was initiated by pressing a button. The automatic course controller then guided the vessel along the predicted curved line, compensating as much as possible for effects of current and wind. Navigators could minimize eventual future deviations by selecting a new desired course and by pushing the button again. The path predictor used in this study was developed by Delft University of Technology (Van Amerongen, 1982; Passenier, 1989). Its design was based upon a relatively simple mathematical ship motion model (Nomoto, Taguchi, Honda & Hirano, 1957) of which the accuracy was increased by continuously adapting its parameters to changing navigational conditions. Extended-Kalman filtering techniques were used to solve the combined state and parameter estimation problem.

With a ground velocity vector, the planned route and ship's true speed vector were shown. Anticipation was based on linear extrapolation of the velocity vector and of the perceived rate of turn. Together with the planned route information this was considered to be a fair navigational support in low rate of turn conditions. However, this was considered to be a moderate navigational support for large course changes.

With parallel-indexing (i.e., navigating on the basis lines, drawn on the radar screen, parallel to the planned route, and positioned on land-fixed radar echos), only the planned route is principally pursued. Compass, rate of turn indicator, and actual ship's position provided minimal means to anticipate the ship's movement with respect to the planned route. This was considered a poor navigational support, particularly for large course changes.
Task performance using basic speed and position information was only expected to be accurate in conditions with limited course alterations; these are situations of sufficient response of the vessel. In that case, preview is essential, as it is provided by a representation of the planned route (G.P). Task performance with basic speed and position information was expected to decrease when large course alterations had to be performed. These are situations where navigators need to anticipate (G.I). Only with path prediction, performance was expected to remain at a high level.

Method

Participants
Twelve fourth-year students from maritime curricula, recruited through the Vlissingen Nautical College, voluntarily participated in the experiment. They had at least one year experience in navigating a merchant vessel. Their age ranged from 20 to 30 years.

Task
The participants were required to sail a 30,000 dwt container vessel along a planned route with a nominal speed of 19 knots. Standard navigation information was used: the planned route, the participant's ship position on a radar screen, ship status information, and meteorological and hydrological data. A Variable Range Marker (VRM) could be selected and manipulated. Moreover, three display types were presented on the navigation display. The participants were instructed to accurately control the vessel along the planned route, performing the course changes with minimum overshoot while maintaining the nominal speed. Course changes were initiated first by selecting a new course with an autopilot (course controller) and then by activating an execute button. Rate of turn limit was fixed at $40^\circ$/min, and the propulsion system was set at 110 rpm. Each planned route consisted of five waypoints with course changes of $15^\circ$, $30^\circ$, $45^\circ$, $75^\circ$ and $105^\circ$, to port or starboard, separated by straight route segments with lengths of 2 or 2.5 nautical miles (nm). There was no other vessel traffic in the area.

Trials were presented in blocks of three. Each block represented a display type, and each trial represented a different planned route composed of five course changes. The average trial time was about 40 minutes.

Apparatus
The experiment was carried out in the TNO-HFRI part task ship manoeuvring simulator; a generic simulator designed to simulate only the relevant task elements of the situation to be investigated. The main elements of the simulator used in this experiment included a mock-
up of an instrumented ship’s bridge, a processor for calculating the control algorithm for autopilot and adaptive path predictor, a graphics processor for the navigation display, and computer systems for model calculation and data storage.

Figure 4.1 Overview of the bridge mock-up and the projected scene in the ship manoeuvring simulator.

The mock-up was a full scale model of the bridge of a commercial vessel (Figure 4.1). The participants were seated at consoles with controls and displays designed for solo watch keeping (Schuffel, Boer & Van Breda, 1989). An integrated navigation display was installed, presenting combined navigation and vessel status information (Figure 4.2). Navigation information consisted of radar information (the participant’s vessel remained in the display centre: relative motion; radar information was north stabilised: north-up) and route information. The planned route was depicted by straight dashed lines connecting the waypoints, and the heading indicator by a dotted line. Several indicators around the edge of the screen presented the vessel state: own ship’s heading and speed, rate of turn, setpoint of the autopilot, rudder deflection and rudder limit. The predicted track ahead for the selected radar range was indicated by a solid line that started at the vessel’s actual position. Three display types were investigated of which details are explained in the next section.
Figure 4.2 The integrated navigation display. Radar information is shown in the screen centre, relative motion, north-up. The planned route is represented by a straight dashed line, the heading indicator by a dotted line. Indicators along the screen edges show the vessel's state variables: ship's heading and speed, rate of turn, setpoint of the autopilot, rudder deflection and rudder limit. This figure shows the basic display suitable for parallel-indexing.

A number of computers was used for the experiment. A PDP11/73 processor was dedicated to the control algorithm for course control and adaptive path predictor, and ensured prediction based on parameter estimation every 2 seconds (Passenier, 1989); a PDP11/23+ computer system was used for scenario generation and on-line data storage; and a PDP11/34 was used for calculating the dynamic behaviour of the vessel. Finally, an IBM PC with graphics processor (pixel resolution 450×780) was used to present information on the integrated navigation display.

The hydrodynamic model of the vessel was based on the manoeuvring characteristics of a second generation 30,000 dwt container vessel (length 225.9 m; draught 11.2 m; propulsion 24,208 kW). A set of equations was used, developed by Brummer, Van de
Chapter 4

Voorde, Van Wijk & Glansdorp (1972), describing the hydrodynamic forces and moment of the ship's hull and the contributions of propeller and rudder. They based the coefficients of the equations concerning the ship's hull on model tests with a planar motion system, the contributions of the rudder on physical equations, and the contributions of the wind forces and moment on towing tests. The estimated time constant of the vessel's rate of turn at a cruising speed of 19 knots was 45 s.

Displays

The following display types were investigated (Figure 4.3):

(i) *path prediction*. Radar information with path prediction, showing the planned route and the ship's predicted track ahead on the navigation display;

(ii) *ground speed vector*. Radar information with the ground speed vector, showing the planned route and ship's true velocity vector;

(iii) *parallel-indexing*. Radar information for parallel-indexing, showing the planned route.

![Diagram of display types](image)

*Figure 4.3 A schematic representation of the three investigated display types: (a) Path prediction, the solid curved line represents the calculated predicted track ahead; (b) Ground speed vector, the straight solid line represents the ship's true speed vector; (c) Parallel-indexing. The dotted line represents the controlled ship's heading, the dashed line the planned route.*

With the path prediction display type, the participant's ship position was shown in the screen centre together with a solid curved line representing the ship's predicted track ahead. Any new selected course on the autopilot was considered a trial course change as long as the execute button was not pressed: the predicted track ahead was then presented as a red solid line. Once the execute button was pressed, the course change manoeuvre was initiated: the predicted track ahead then changed into a solid black line. Orientation of the display information was north-up, relative motion. The predicted track ahead was shown over the total radar range. With the ground speed vector display type, the participant's ship position
was shown with a vector, representing the ship's actual true speed vector. The vector length was three minutes. With the parallel-indexing display type, the participant's ship position was shown.

Procedure
Pairs of participants took part in the experiments on two consecutive days. On the first day they had to perform practice trials under close supervision of the experimenter. The display types were explained and familiarization trials were performed. On the basis of pilot studies, it was determined that about two hours of practice was sufficient to obtain a stable performance level from each participant. Thereafter, the experimental trials were started: there were three trials for each display type, each trial representing a planned route with five course changes. Display types were presented in balanced order; the course changes were randomized.

Performance measurements
The state variables, including position, heading, speed, rate of turn, autopilot setpoint, and rudder deflection, were sampled and stored every 2 seconds. Performance was recorded in terms of position error and rate of turn variability, indicating navigation accuracy and control effort, respectively. Position error was defined as the root-mean-square (RMS) distance error between actual path and planned route, expressed in m, calculated over route segments within 2600 m of the waypoints, and corrected for the inherent manoeuvring characteristics of the vessel. Rate of turn variability was defined as the standard deviation, expressed in °/s.

Results

Position error
An ANOVA on the position error, with display type (path prediction, ground speed vector, or parallel-indexing) and course change (15°, 30°, 45°, 75°, or 105°) as independent variables, showed a main effect of display type \( F(2,22) = 65.6; p < .0001 \); explained variance 15.9% and course change \( F(4,44) = 36.8; p < .01 \); explained variance 18.1%. Figure 4.4 shows the position error as function of display type and course change, averaged across participants.
Figure 4.4 Position error (RMS distance error) as a function of display type and course change, averaged across participants. The three investigated display types were: (a) path prediction, (b) ground speed vector, and (c) parallel-indexing.

The main effect of display type revealed that the position error was considerably smaller with path prediction (i) than with ground speed vector (ii) or parallel-indexing (iii) display information. The average position error was 33 m with path prediction (i), 95 m with ground speed vector (ii) and 117 m with parallel-indexing (iii) display information. A post-hoc Newman-Keuls comparison test showed path prediction display type (i) to be significantly different from ground speed vector (ii) and parallel-indexing (iii) display types ($p < .01$).

The main effect of course change on position error indicated increasing position error with larger course changes. The average position error at a 15° course change was 38 m, while at 105° course change the position error was 125 m. A significant interaction was found between display type and course change, $F(8,88) = 6.0; p < .01$; explained variance 3.9%. All display types resulted in a relatively small position error when course changes up to 45° were performed. For large course changes the position error increased considerably, particularly when ground speed vector (ii) and parallel-indexing (iii) display information were used. A post-hoc Newman-Keuls test indicated no difference in position error between the display types for course changes up to 30°. With path prediction (i) no difference in position error was found between all course changes.
**Experiment 3: Ship guidance with preview and path prediction**

**Standard deviation rate of turn**

An ANOVA on the standard deviation of the rate of turn, with display type (path prediction, ground speed vector, or parallel-indexing) and course change (15°, 30°, 45°, 75°, or 105°) as independent variables, showed a main effect of display type \(F(2,22)=8.1; p < .01\); explained variance 0.6\%] and course change \(F(4,44)=303.0; p < .0001\); explained variance 55.5\%]. Figure 4.5 shows the standard deviation of the rate of turn as a function of display type and course change, averaged across participants.

![Graph showing standard deviation rate of turn](image)

Figure 4.5 Standard deviation of the rate of turn as a function of display type and course change, averaged across participants. The three investigated display types: (a) path prediction, (b) ground speed vector, and (c) parallel-indexing.

The main effect of display type indicated that the standard deviation of the rate of turn differed significantly between the display types. In average the rate of turn was 0.20°/s with ground speed vector (ii) and with parallel-indexing (iii) display information, whereas with the path prediction (i) this was 10% less. A post-hoc Newman-Keuls comparison test indicated only ground speed vector to be different from both the other display conditions \(p < .05\).

The main effect of course change on standard deviation of the rate of turn revealed increasing standard deviation of the rate of turn with larger course changes. The average standard deviation of the rate of turn was 0.12°/s at a 15° course change and was 0.19°/s at a 105° course change. Maximum rate of turn was measured during 45° and 75° course change.
change manoeuvres, 0.24°/s and 0.27°/s, respectively. A significant interaction was found between display type and course change, \(F(8,88)=0.49; p < .01\); explained variance 1.9%. A post-hoc Newman-Keuls test indicated that this was mainly due to differences in the 75° and 110° course change manoeuvres \((p < .01)\).

Discussion

The potential benefits of predictive information for ship control in routine task conditions were demonstrated in this experiment, using a track keeping task. It was found that the use of path prediction improved ship control accuracy considerably, particularly when large course changes were performed. In that case, 70% reduction in position error (RMS distance error) was found as compared with both the other display types. The inaccuracy of manoeuvring that occurred for large course changes with ground speed vector and parallel-indexing was expected. In these manoeuvring conditions, additional support in anticipation was needed but not provided. Hence, path prediction was effective in supporting anticipation: the position error remained at a constant low level for all course changes.

The effect of display type on the rate of turn variability showed increasing standard deviation of the rate of turn with increasing course changes up to 75°. For these course changes, no difference was found between the display conditions which indicates that the same control effort was made for all display types. Real differences appeared for the 105° course change manoeuvres; maximum rate of turn variability was then found when the parallel-indexing display information was used, and minimum rate of turn variability with both the other display types. The fact that participants did not have the least rate of turn variability when they used path prediction may be due to their capability in detecting future lateral deviations in a very early stage of the manoeuvre. Frequent corrections may have increased the standard deviation of the rate of turn.

Conclusion

Results of the experiment show that combined preview and path prediction information effectively supports anticipation in routine supervisory control (guidance function), when rapid tasks are performed. Expectation 2 was confirmed.
Chapter 5

Experiment 4: Ship navigation with preview and path prediction

Abstract — In an experiment, Expectation 2 was tested in non-routine task conditions (navigation function). The experimental conditions were more or less identical to Experiment 3, however, in order to test the statement in Expectation 2 that preview and path prediction information are effective to support only (routine) guidance functions, non-routine task conditions were created by introducing unexpected events in the simulator scenarios. The experimental setup was such that a sudden passing manoeuvre had to be performed due to an unexpected obstruction of the fairway. For passing manoeuvres with small course alterations, control performance was estimated to depend primarily on the ability of the navigator to perceive the course of the fairway. This requires preview information (G.P). For passing manoeuvres with large course alterations, control performance was estimated to depend primarily on the ability of the navigator to anticipate (G.I). For preview support, a representation of the planned route was shown on a navigation display. For anticipation support, predictive information was presented: Path prediction based on extrapolation, or path prediction based on fast time model calculations. Task difficulty varied with the need of control effort during the passing manoeuvre. Task performance was assessed in terms of tracking accuracy.

Results of the experiment show that control performance decreased with increasing task difficulty. Particularly when extrapolators were used for path prediction, a considerable loss of performance occurred. Expectation 2 was not confirmed.

Introduction

Manoeuvring a deep draught vessel in an approach channel puts high demands on the quality of the human-ship system. For the navigator there are two typical aspects: dealing with a limited manoeuvring area and dealing with the typical manoeuvring characteristics of

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4 This Chapter has been published as:
such a vessel. Since visual navigation is no longer sufficient to guarantee safe passage through a channel, pilots currently use an electronic harbour approach system (Van der Ent, 1991). The system that is used at Europort Entrance Hook of Holland is the so-called Brown Box (BB), a portable radio navigation system for deep draught vessel pilotage. Unfortunately, this BB has a limited accuracy: the resolution of the position fixing is limited and the stability tends to fluctuate considerably. New technological developments in the fields of satellite navigation systems and geographical information systems offer the possibility of replacing the current BB system with a more accurate and flexible harbour approach system. Such a system could, for instance, be based on Differential GPS, a position information system which is currently being tested at Europort Entrance Hook of Holland. A new BB with increased accuracy could improve the navigational accuracy considerably, particularly when a path prediction function is added. Implementation of that function in the design of a new BB may then be considered.

The goal of this study was to investigate whether combined preview and path prediction information supports anticipation in non-routine navigation tasks as well. According to Expectation 2 this will not be the case. Experimental conditions were created more or less identical to Experiment 3, however, at a certain moment during the guidance task, an unexpected event occurred. In this case, the fairway was blocked, and the navigator were forced to accurately perform a predetermined passing manoeuvre. Therefore, new route segments appeared on the navigation display, representing a dual course change manoeuvre to be executed. On the ship’s bridge, standard navigation instruments were available, supplemented with one of the following path prediction display types:

(i) speed-rotation-inertia path prediction. Path prediction was obtained by fast-time calculation of an exact copy of the vessel’s hydrodynamic model. Since this incorporated a complete mathematical description of the vessel’s dynamic behaviour, including inertia and effect of wind and current, an accurate prediction of the vessel’s future track ahead was obtained with the assumption that wind and current remain the same. The model was updated on a regular basis (e.g., every 1 second) with the current status of the vessel;

(ii) speed-rotation extrapolation. Path prediction was obtained by extrapolating the momentary speed and rate of turn of the vessel. The prediction model did not incorporate the vessel’s inertia, but rather assumed that the actual speed and rate of turn of the vessel, including effects of wind and current, would remain the same. Note that such a path predictor is accurate as long as speed and rate of turn are more or less constant. However, the vessel’s behaviour is heavily affected by higher order (acceleration) components when sudden manoeuvres are performed, which causes the prediction to be less accurate. In particular long term predictions may then be inaccurate;
Experiment 4: *Ship navigation with preview and path prediction*

(iii) *speed extrapolation*. Path prediction was obtained by linear extrapolation of the vessel's momentary ground speed vector. This is a standard provision in modern Automatic Radar Plotting Aid (ARPA) systems. Navigating with this path predictor was therefore considered as the reference condition.

Performance was expected to be very accurate during passing manoeuvres with limited course changes. Preview information is then required, as was provided by a representation of the planned route on the navigation display (G.P). Control performance was expected to deteriorate rapidly with increasing magnitude of the course change manoeuvre. Rules-of-thumb cannot be used because corrective actions frequently comprise multiple control actions, e.g., counter-rudder actions. A representation of the predicted track ahead, particularly extrapolator-based path prediction, does not provide that type of information, while navigators generally lack this knowledge. Navigational performance was therefore expected to decrease, in all investigated circumstances.

Furthermore, best performance was expected with accurate path prediction, i.e., with prediction type (i). Navigational support was expected to be less effective with extrapolator type (iii). By adding rate of turn to the extrapolator — prediction type (ii) is considered as an extension of prediction type (iii) — additional anticipation support is provided. It was therefore expected that the navigational performance with prediction type (ii) would be somewhere in between the navigational performance with prediction type (i) and (iii). This experiment will point out to what extent this compromise between optimal, model-based prediction, and extrapolation-based prediction will be suitable to support the navigation task.

Performance was measured in terms of navigational accuracy, defined as deviation from the planned route. For that purpose, control actions and the vessel's state variables were recorded.

**Method**

**Participants**
Six channel pilots participated in the experiment. They were all experienced Europort Channel pilots. Their age ranged from 43 to 53 years, and their piloting experience ranged from 14 to 24 years.
Task
Each participant was required to accurately sail a deep draught vessel (280,000 dwt) in a simulator with a nominal speed of 7 knots along a planned route. Standard navigation information was available on different display systems, i.e., planned route, participant’s ship position and position of other vessels on an ARPA radar screen; ship status information, meteorological and hydrological data on a separate screen. The participant’s vessel predicted track ahead was presented on the radar screen, starting from the actual position. In each experimental trial, the vessel initially followed a straight route. The course to steer was compensated for wind and current effects, allowing the participant to carefully observe the instruments and the outside world scene. Then, a short-term passing manoeuvre had to be performed, of which the route was presented on the navigation display. The participants were instructed to control the vessel as accurately as possible along the indicated route, passing straight between a first pair of buoys, then performing the course change while following the indicated route, and finally passing straight between a second pair of buoys. The longitudinal distance between the first and second pair of buoys was 0.5 nm, the lateral distance was 0.19 nm. The course change of the passing manoeuvre varied: 10°, 20°, 30°, 35° or 40°, to port or to starboard. There was no wind, and the current was 2.5 knots in a direction of 45°, 135° or 270°, balanced over the experimental conditions. Each trial ended when the vessel had passed the second pair of buoys. The vessel was only controlled by helmsman’s orders. No propulsion orders were allowed.

Trials were presented in blocks of five. Each block represented a path prediction display type, within which each trial was a different course change of the passing manoeuvre. To avoid confusion, an additional practice trial was performed each time a new block was started. The average trial time was about 12 minutes.

Apparatus
The experiment was carried out in the TNO-HFRI ship manoeuvring simulator. This simulator consisted of an image generator with projection system, a mockup of an instrumented ship’s bridge, and computer systems with a hydrodynamic model of the vessel.

Image generator and projection system were the same as used Experiment 1. The mockup was a partially instrumented bridge of a modern vessel. The participants were seated at consoles equipped with controls and displays for navigation and status surveillance. On the ARPA navigation display, radar information was shown, relative motion, north-up (Figure 5.1).
Figure 5.1 The navigation display showing the radar image and the ARPA functions controllable with soft buttons on the right hand screen edge. The segmented dashed line is the planned route containing two waypoints, the dotted line represents vessel’s heading line. The solid curved line is the predicted track ahead, here obtained from the speed-rotation-extrapolator.

The planned route was depicted by straight dashed lines connecting the various waypoints. Along the right hand screen edge, soft push buttons provided interaction with a menu for changing the radar display settings and with windows for general ARPA information presentation, such as own ship’s heading; speed; target range; bearing; speed; course; passing distance; and time. A Variable Range Marker (VRM) and Parallel-Index (PI) lines could be selected and manipulated. The predicted track ahead, presented in the screen centre and starting in the vessel’s centre of gravity, indicated the future track over the next 10 minutes. This equated to the time that each experimental trial would last. Three path prediction types were investigated, details of which are given in the next section. The status display showed the vessel’s state variables, as: actual heading, rate of turn, rudder deflection, speed, propeller revolutions, absolute wind and current data, and time of day. An
intercom system was installed for passing rudder orders to the helmsman. The participants were told not to use the engine telegraph system, since the setting of the propulsion system remained the same during the experiment.

For the current experiment, a simplified multi-variable model was used that describes the vessel's speed and rate of turn during manoeuvring (De Keizer, 1977). The parameters of this model were derived from a hydrodynamic model of a 280,000 dwt deep draught tanker (Abkowitz, 1980). The estimated time constant of the vessel's rate of turn at a 7 knots cruising speed was 250 s.

**Path prediction**

Three path prediction types were investigated (Figure 5.2):

(i) *the speed-rotation-inertia path prediction*. The predicted track ahead was presented as a curved line. Since the prediction model included the vessel's inertia, effects of changes in rudder angles on the ship's predicted track ahead were calculated and presented immediately. The predicted track ahead instantaneously appeared on the screen each time a rudder order was given and remained unchanged as long as the same rudder angle was maintained. The prediction was highly accurate and included higher order effects, i.e., accelerations of the vessel. For instance, a manoeuvre with decreasing rate of turn resulted in a spiral shaped predicted track ahead with an increasing radius of the curvature; a predicted track ahead to port could even merge into a predicted track ahead to starboard;

(ii) *speed-rotation extrapolation*. Extrapolation included the momentary forward speed and rate of turn of the vessel, not taking into account the vessel's inertia. This resulted in a circular predicted track ahead. Changes in rudder angle caused the predicted track ahead to change slowly: the radius changed as long as the rate of turn of the vessel varied. For instance, a manoeuvre with decreasing rate of turn showed a circular shaped predicted track ahead; a predicted track ahead to port could not merge into a predicted track ahead to starboard;

(iii) *speed extrapolation*. The predicted track ahead was presented as the ground speed vector.
Experiment 4: Ship navigation with preview and path prediction

Figure 5.2 Examples of the predicted track ahead, obtained by (a) speed-rotation-inertia path prediction, (b) speed-rotation-extrapolation, and (c) speed-extrapolation. This figure shows a situation in which the vessel is turning to port side while the navigator performs a counter-rudder action to starboard side.

Procedure
The experiment took a single day for each participant. In an introduction session, the principle of the simulator was explained, followed by three blocks of practice trials for familiarization with each path prediction display type. Each practice trial lasted 30 minutes. In this session, the order was (iii), (ii), (i): the participants started in the reference condition and then performed trials with both the higher order predictors. Earlier pilot studies had revealed that this amount of trials was sufficient to obtain a stable level of performance from each participant. After completion of the practice trials, the experimental trials were performed: 3 blocks of 5 trials. Each block represented a path prediction condition, each trial a different course change of the passing manoeuvre. The course changes were presented in balanced order. To avoid confusion, an additional practice trial was performed at the beginning of each new block. Each experimental trial lasted about 12 minutes.

Performance measurement
State variables position, heading, speed, rate of turn and rudder angle, were sampled and stored at 1 second intervals. Performance was recorded in terms of navigation accuracy and navigation effort. Navigation accuracy was expressed in terms of position error and direction error, navigation effort in terms of rudder deflection and rudder calls. The position error was defined as the RMS distance error between the actual sailed path and the planned route, expressed in metres; the direction error was defined as the absolute deviation and the RMS deviation between the direction of the actual ship’s path and direction of the planned route, expressed in degrees. The measures were taken along route segments over a length of 0.1 nm, half way the passing manoeuvre and between the second pair of buoys.
Rudder deflection was defined as the RMS rudder deflection, expressed in degrees; and the rudder calls, both over the total duration of the passing manoeuvre.

Results

Position error
A within-subject ANOVA on the position error, with path prediction type (speed-rotation-inertia path prediction, speed-rotation-extrapolator, or speed-extrapolator) and course change of the passing manoeuvre (10°, 20°, 30°, 35°, or 40°) as independent variables, showed a main effect of display type and course change, $F(2,10)=12.0$; $p<.01$; explained variance 27.9%, and $F(4,20)=3.8$; $p<.05$; explained variance 7.9%, respectively. This result means that the position error was different for the various path prediction types and for the course changes. Figure 5.3 shows the mean position error as a function of path prediction and course change, averaged across participants.

![Graph showing position error as a function of path prediction type and course change](image_url)

Figure 5.3 Position error (RMS distance error) as a function of path prediction type and course change of the passing manoeuvre, averaged across participants. The investigated path prediction types: (a) speed-rotation-inertia path prediction, (b) speed-rotation-extrapolator, and (c) speed-extrapolator.
The main effect of path prediction type on the position error indicated that smallest values were obtained with path prediction (i) and path prediction (ii), and the largest with path prediction (iii). The mean position error with path prediction (i) and path prediction (ii) was 28.0 m and 42.3 m, respectively (in average 35 m), with path prediction (iii) this was 76.3 m. A post-hoc Tukey comparison test showed path prediction (iii) to be different from path prediction (i) and path prediction (ii), with $p < .01$ and $p < .05$, respectively. No difference was found between the position errors with path prediction (i) and path prediction (ii). The main effect of course change on position error was as expected: the mean position error increased with larger course changes, being about 30 m with course changes 10° and about 60 m with course changes 40°. No interaction was found between path prediction and course change ($p = .14$).

**Direction error**

An ANOVA on the mean direction error (absolute deviation), with path prediction type (speed-rotation-inertia path prediction, speed-rotation-extrapolator, or speed-extrapolator) and course change of the passing manoeuvre (10°, 20°, 30°, 35°, or 40°) as independent variables, showed a main effect of prediction type and course change, $F(2,10)=9.5$; $p < .01$; explained variance 10.7%, and $F(4,20)=6.0$; $p < .01$; explained variance 11.7%, respectively. Figure 5.4 shows the mean direction error as a function of path prediction and course change, averaged across participants.

The main effect of path prediction on the direction error showed a considerably larger direction error with path prediction (ii) and path prediction (iii) than with path prediction (i): in average this was 15°, 13°, and 8°, respectively. This means that the direction error was reduced by about a factor of two when path prediction (i) was used. A post-hoc Tukey test indicated path prediction (i) to be different from path prediction (ii) and path prediction (iii), $p < .05$ and $p < .01$, respectively. The main effect of course change on the direction error corresponded largely with the main effect on position error: the direction error was about 7° with small course changes, increasing to about 17° when large course changes were performed. No interaction between path prediction and course change was found.

An ANOVA on the mean direction error (RMS deviation), with path prediction type (speed-rotation-inertia path prediction, speed-rotation-extrapolator, or speed-extrapolator) and course change of the passing manoeuvre (10°, 20°, 30°, 35°, or 40°) as independent variables, showed a weaker main effect of prediction type, $F(4,20)=7.2$; $p < .05$; explained variance 11.2%. The main effect of course change was $F(2,10)=5.4$; $p < .01$; explained variance 11.1%. A post-hoc Tukey comparison test showed path prediction (i) only to be different from path prediction (iii).

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Figure 5.4 Direction error as a function of path prediction and course change, averaged across participants. The investigated path prediction types: (a) speed-rotation-inertia path prediction, (b) speed-rotation-extrapolator, and (c) speed-extrapolator.

**Rudder deflection**

An ANOVA on the rudder deflection, with path prediction type (speed-rotation-inertia path prediction, speed-rotation-extrapolator, or speed-extrapolator) and course change of the passing manoeuvre (10°, 20°, 30°, 35°, or 40°) as independent variables, only showed a main effect of course change, $F(4,20)=4.7; p<.01$; explained variance 10.5%. The mean rudder deflection increased when larger course changes were performed, being 17° for course changes of 10°, and 24° for course changes of 40°. The mean rudder deflection with path prediction (i), path prediction (ii), and path prediction (iii) was 18.7°, 20.8° and 24.5°, respectively. The ANOVA on the rudder calls did not show any main effect. It appeared that in average fewest rudder calls were given when path prediction (iii) was used, and most rudder calls when path prediction (i) was used, 6.2 and 9.2, respectively. This difference was not significant due to the large standard deviations, being 3.2 with path prediction (i), 5.8 with path prediction (ii) and 3.2 with path prediction (iii), respectively.
Experiment 4: *Ship navigation with preview and path prediction*

**Discussion**

The potential benefits of predictive display information for accurate ship navigation in non-routine task situations was investigated in a simulator study, utilizing a short-term passing manoeuvre to be performed with a channel-bound vessel. It was found that the best navigational performance was obtained when navigators used path prediction based on a prediction model that contains an exact copy of the manoeuvring characteristics of the controlled vessel. For all passing manoeuvres this resulted in a mean position error (RMS distance error) of about 30 m and a mean direction error of 8°. Navigating with path prediction information based on extrapolators affected negatively the navigational performance. With a speed-rotation-extrapolator, the same mean position error was obtained, but the mean direction error nearly doubled; with a speed-extrapolator the mean position error increased to 75 m and the mean direction error to 15°. This means that minimal position error was obtained as long as the navigator was supported by a path predictor that included the state variables forward speed and rate of turn in the predictive model. This was the case with path predictions (i) and (ii) which produced a position error, on the average, of 35 m, being nearly 50% of the position error in the speed-extrapolator case. However, navigating with path prediction (ii), and to a certain extend with path prediction (i), resulted in a considerable direction error which indicated loss of controllability by the participants. Analysis of the control behaviour confirmed the findings of Experiment 3; there was a tendency that smallest rudder deflections were given in case the most accurate path predictor was used, however, these rudder deflections consisted of many small corrective rudder calls.

The experimental results also showed performance decrease with increasing magnitude of the course change manoeuvre. Participants were able to accurately follow the planned route when small course changes were performed. The perceived movements of the vessel provided adequate feedback to the navigator, minimizing the need for additional support. Large course changes, however, caused the navigational performance to degrade. Most accurate control was obtained with path prediction (i), a predictor based on a prediction model that contained an exact copy of the model used to describe the controlled ship’s motions. Interestingly, control performance with predictor (ii) was comparable to path prediction (i). Apparently, extrapolation of speed and rate of turn information enabled effective anticipation of the navigator. In this respect, Jensen (1981) and Roscoe, Corl & Jensen (1981) found comparable results in aircraft control. They argued that prediction displays based on speed information provided little help when a curved route was followed. Speed information was estimated to be only useful as an indicator for drift, helping to reduce lateral steering error in circumstances with cross-disturbances, particularly on straight segments of a route; adding turn-rate information improved the steering perfor-
mance along a curved route. Unfortunately, no comparable quantitative results were available on this matter.

Since it was found that control accuracy had a tendency to decrease during large course changes, it can be concluded that it is still possible to improve task performance. For instance, in Experiment 3 navigators were dealing with an interactive prediction display which enabled them to perform predictive trials and thus to explore the manoeuvring capabilities of the vessel. This resulted in a constant high level of performance. In the present experiment this was not the case: the predicted track ahead was depicted as a single track based on the actual state of the vessel. This obstructed optimal judgement of the vessel's manoeuvring capabilities. In the current experiment, short-term counter rudder actions were frequently required, which introduced considerable changes in the system's state. Effects of these changes were not considered by the path predictions used in the current experiment. Further investigation is recommended on the benefits of additional provisions, e.g., information showing the effect of multiple rudder actions by means of a so-called ship's capability envelope, indicating the total manoeuvring area. This provides more insight into the capabilities and limitations of the total ship system.

The analyses also revealed that some of the participating pilots had difficulties in performing the experimental trials. A channel pilot is an experienced navigator who has profound knowledge of how to control large vessels along a planned route. He knows the manoeuvring characteristics of the vessel and uses navigation tables and simplified formulas (rules of thumb) to determine the wheel-over-point. In the present experiment there was not enough time to do this, since the experimental conditions were based on more or less unexpected events. This seriously hampered their navigation task.

In the current study, the best possible predictor is described; an exact copy of the model describing the ship's motion in the simulator was used. For practical applications this is not realistic. Simple implementation of path prediction in a portable system may be obtained by using extrapolators because they operate on the basis of a limited quantity of sampled sensor data. In practice, however, it is questionable whether sensors provide signals with sufficient accuracy.

**Conclusion**

Results of the experiment show that preview and path prediction information do not fully support anticipating behaviour in non-routine navigation tasks. Particularly in conditions
Experiment 4: *Ship navigation with preview and path prediction*

where path prediction was based on extrapolation, a considerable loss of performance occurred. Expectation 2 was not confirmed.

For adequate support, it was advised to add provisions that indicate the capability envelope of the vessel, i.e., a representation of the total predicted manoeuvring area of the vessel, showing the capabilities and limitations of the total ship system.
Chapter 6

Experiment 5: Ship navigation with preview and capability prediction

Abstract — In an experiment, Expectation 3 was tested: Preview and path prediction information, in combination with information representing the predicted manoeuvring margins — the so-called Predicted Capability Envelope (PCE) — support non-routine navigation. A route following task in a ship manoeuvring simulator was chosen, where navigators had to cross a busy traffic separation scheme with a medium size vessel. They were told to keep other vessels at a predetermined minimum safety distance (1 nm). Traffic situation initially was such that no course or speed alterations were required to proceed. Then, an unexpected change in the traffic situation occurred, causing collision danger. The navigator first had to select an alternative safe route (N), and then guide the controlled vessel along that alternative route (G, C). Integrated predictive information was used to support the navigator, consisting of predictions indicating the total manoeuvring margins of the controlled vessel considering the manoeuvring capability of the vessel with respect to fairway and other traffic ships (PCE), with additional preview and path prediction information. Predictive information indicating the total manoeuvring margins of the controlled vessel directly shows alternative safe routes on the display (N,P). Selecting the proper alternative route is then a matter of considering the margins for safety together with economical criteria (N,I). Once the alternative route is chosen (N,E), task execution concerns guidance and control (G, C), with preview and path prediction support. A combination of capability prediction, preview and path prediction was expected to fully support the navigator’s anticipating behaviour, leading to safe guidance and control. Navigational task performance was determined when navigators used standard collision avoidance radar information (ARPA), with or without PCE. Experimental trials were performed under normal and under high-workload task conditions. Performance was assessed in terms of safe and efficient navigation.

Results of the experiment show that there was a significant improvement in navigation performance when PCE information was used, with preview and path prediction. Compared with the basic ARPA radar information, significantly fewer violations of the minimum safety distance occurred. In the investigated task conditions this was a factor of four. PCE as an addition to ARPA was found to provide maximum anticipation support. Expectation 3 was confirmed.

5 This Chapter has been published as:
Introduction

In Experiments 3 and 4 it was demonstrated that path prediction mainly supports supervisory control in routine task conditions. Because path prediction only shows a curved line on the screen, representing the predicted track ahead of a vessel considering the current control settings, anticipation is only partially supported. In fact, navigators are not aware what the ship’s future track ahead would be when the vessel’s state is changing, i.e., when other control settings are used (e.g., in case of counter-course control during a passing manoeuvre). This hampers the navigator’s optimal use of the manoeuvring capabilities of the vessel. It was remarked that provisions for a trial manoeuvre would better support the navigator’s anticipation by providing more insight into the ship’s manoeuvring capabilities and limitations. A model based concept was chosen, taking dependencies between control (rudder) and effectiveness (resulting thrust) parameters into account. This involves calculation and presentation of the total manoeuvring margins of the vessel on the basis of multiple process tuning predictions — we call this Predicted Capability Envelope (PCE) — on a navigation display, instead of a single predicted track ahead based on the current control setting. The predicted margins include restrictions due to fairway boundaries and due to other traffic ships. The PCE represents the complete reach of the controlled vessel for a particular time horizon. By intersecting the PCE with a required minimum safety distance (e.g., 1 nm), an integral representation of (other traffic) threats and (controlled ship) capabilities is obtained. Based on the assumption that course and speed of other ships remain the same, the presented threats will be geographically stable areas. Navigators may consider these as obstacles in the fairway. Thus, an integrated navigation display is obtained, providing an overview of the ship’s manoeuvring and collision avoidance information for a particular navigation task condition.

The goal of the current experiment was to test the expectation that preview and path prediction information, in combination with PCE information, support non-routine supervisory control tasks (navigation tasks) (Expectation 3). In a ship manoeuvring simulator, navigators had to follow a route across a busy traffic separation scheme with a medium size vessel. They were told to keep other vessels at a predetermined minimum safety distance (1 nm). This was considered a highly demanding task, since high-density traffic situations may then be expected. To maintain the voyage plan, it is essential that navigators keep safe distance to other traffic ships while maintaining course and speed as much as possible. These ships approached from port and from starboard side. Vessel traffic initially was such that no course or speed alterations were required in following the planned route. Then, an unexpected change in the traffic situation occurred, for instance, because one of the traffic ships changed its speed, causing collision danger. In this case, navigators cannot just
Experiment 5: Ship navigation with preview and capability prediction

perform a passing manoeuvre to avoid the problem; course alterations could lead to collision risk with other traffic ships, or, cause the ship to exceed the fairway boundaries. To solve the problem situation, alternative safe routes for navigation must be considered and selected first. PCE information was expected to facilitate the selection of these alternatives, considering the voyage plan, the safety regulations, traffic rules, and fairway boundaries. By presenting PCE information in combination with preview and path prediction, full anticipation support is provided.

Three navigation display types were investigated:
(i) a standard ARPA radar display, providing basic traffic and collision avoidance information. Because this concerned existing navigation systems, this was considered the baseline display type;
(ii) a standard ARPA radar display with additional PCE based on constant propulsion of the navigator's vessel, providing information about safest course to proceed;
(iii) a standard ARPA radar display with additional PCE based on a variable propulsion of the navigator's vessel, providing information about the safest course and speed to proceed.

Workload task condition was manipulated to provide a systematic comparison between the display types in different navigation conditions.

Task performance was expected to be best in conditions where PCE was used. PCE information shows the total manoeuvring margins of the controlled vessel as well as the safe areas to proceed. Selecting the safest alternative route is then a matter of considering the presented safety margins. Once the alternative route is selected, task execution only concerns guidance and control, with preview and path prediction support. The use of a speed selection option was expected give the best results.

Method

Participants
Twelve fourth-year students from maritime curricula (Vlissingen Nautical College) participated voluntarily in the experiment. All students had finished their year of practical training.

Task
Each participant was required to sail a 110,000 dwt tanker in a ship manoeuvring simulator along a planned route, crossing an East-West traffic separation scheme. The lanes of the scheme were 1.5 nm wide, separated by a 0.5 nm zone.
The participant's vessel started 3 nm from the centre line of the separation zone, with an nominal speed of 15 knots. Traffic vessels were approaching from port side in the first lane to cross, and from starboard side in the second lane to cross. The traffic lanes were in the direction 90° and 270°. The participant's vessel initially followed a crossing lane in direction 0° or 180°. A night scene was created; navigation lights and traffic signals were visible in the external world scene of the simulator. Normal safety and navigation rules (Rules of the Road) with respect to other vessels and traffic signals had to be followed. The participants were required to cross both lanes and to follow the planned route as much as possible, while looking outside and considering information presented on the navigation display. For safe navigation, it was of primary importance that a 1 nm minimum passing distance to other ships was maintained. Collision avoidance manoeuvres could be initiated by performing a course change or by adjusting the speed of the vessel. Each experimental trial ended after 20 minutes.

Trials were executed under normal, and under high-workload conditions. High-workload task conditions were created by presenting a so-called continuous memory task (CMT) to the participants, in addition to the navigation task. A CMT consisted of a letter-detection task that was presented by headphones, one letter each 1.5 s. The participants were required to press a button each time they recognized one out of four target letters. In addition, the number of target letters had to be counted in separate tallies. The button had to be pressed twice every time a target letter was repeated. The total duration of the CMT was 3 minutes. Normal workload task conditions were created when the CMT was absent.

Trials were presented in three blocks of four, each block representing a display type. The normal and high-workload task conditions were presented in balanced order.

**Apparatus**

The experiment was carried out in the TNO-HFRI ship manoeuvring simulator. The simulator consists of an image generator with projection system, a mock-up of an instrumented ship's bridge, and computer systems with a hydrodynamic model of the vessel. Image generator and projection system were the same as used in Experiment 4.

The mock-up was a partially instrumented bridge of a modern tanker. Participants were seated at consoles equipped with controls and a navigation display. For course control, an autopilot system was installed. The participants first had to select a new desired course, then start the execution of the course changing manoeuvre by pushing an execute button. Maximum rudder deflection could be selected to limit the rate of turn. A push button telegraph system was used to select the propulsion setting (revolutions of the propeller shaft); '0' for stop, and '110' for full ahead. An intercom system was used for speech
Experiment 5: Ship navigation with preview and capability prediction

communication between experimenter and bridge mock-up. The minimum rudder limit was pre-set at 10°.

The hydrodynamic model of the vessel was derived from an accurate manoeuvring model of a 110,000 dwt tanker. For the experiment, this model was simplified to a multi-variable model (De Keizer, 1977) with which relevant non-linear manoeuvring effects in terms of speed and rate of turn could be reproduced. The estimated time constant of the vessel’s rate of turn at a cruising speed of 8 knots was 107 s. For calculation of the predictions, the same model was used.

Displays

Three navigation display types were investigated:

(i) ARPA. Basic radar and collision avoidance information, the reference condition;
(ii) ARPA/PCE/course. ARPA information, supplemented with PCE based on constant propulsion of the navigator’s vessel, providing information about safest course to proceed;
(iii) ARPA/PCE/course/speed. ARPA information, supplemented with PCE based on variable propulsion of the navigator’s vessel, providing information about safest course and speed to proceed.

With the ARPA display type, basic radar and collision avoidance information was presented on the navigation display, in relative motion, north-up mode (Figure 6.1). The ship’s fairway was visible as an electronic chart superimposed on the radar picture, with the planned route depicted as a solid green line. Other vessels were shown as targets. Along the right-hand screen edge, a menu for display interaction was presented, showing ‘soft’ push buttons for the radar display setting, and windows for general collision avoidance information such as heading and speed of the participant’s vessel, radar range, range ring distance, and vector length. Variable range marker (VRM) and parallel-index (PI) lines could be selected and manipulated. A cursor was always presented on the screen; range and bearing of its position were continuously presented in a separate window. This cursor could also be used to select targets for collision avoidance information. The selected target would start to blink amber while the target’s range, bearing, speed, course, minimum passing distance (closest point of approach, CPA) and time to minimum passing distance (TCPA) were presented. Targets were always plotted in a selectable mode (i.e., true or relative vector mode). Along the screen edges, indicators for vessel’s state variables were presented: actual heading, selected course, rate of turn, rudder deflection, log speed, revolutions of the propeller shaft, absolute wind and current data, and time of day. Interaction with the navigation display was performed by a separate mouse. The ARPA display type was considered the baseline task condition.
Figure 6.1 The ARPA navigation display. Basic radar and chart information with collision avoidance information on the right. Radar information is surrounded by vessel status information presented in scales. The controlled vessel position is the screen centre. Radar echos are plotted automatically.

With the ARPA/PCE/course display type, basic ARPA radar and collision avoidance display information was supplemented with PCE information (Figure 6.2):

- a black line representing the vessel’s actual heading;
- an amber line representing the predicted track ahead over the next 30 minutes, given the selected radar range and heading set point of the autopilot (course controller);
- a black dotted line representing a trial value for a new heading setting, selectable by turning the selector of the autopilot;
- a black contour line representing the vessel’s inherent manoeuvring area: within maximum (30°) rudder deflection, and within 110° course change. The maximum prediction time (time horizon) was 30 minutes. For each predicted track it was calculated whether the minimum safety distance of 1 nm from any of the traffic vessels was violated. For
Experiment 5: *Ship navigation with preview and capability prediction*

these tracks, a linear extrapolation technique was used, assuming a fixed speed and course of all targets (in accordance with conventional CPA calculations);
- red zones representing the no sail through zones and indicating areas with a passing distance less than 1 nm; dark red zones representing areas with a passing distance less than 0.5 nm.

![Diagram](image)

Figure 6.2. The ARPA/PCE/course navigation display. The basic ARPA display is supplemented with Predicted Capability Envelope (PCE) information based on constant propulsion of the navigator's vessel:
- a black line representing the vessel's heading line;
- an amber line representing the vessel's predicted track ahead (30 minutes prediction);
- a black dotted line representing a trial value for a new heading setting;
- a black contour line representing the vessel's inherent manoeuvring area;
- red zones indicating areas with a passing distance to other traffic ships less than 1.0 nm; dark red zones represent areas with a passing distance less than 0.5 nm.

With the **ARPA/PCE/course/speed** display type, basic ARPA radar and collision avoidance information was supplemented with PCE, and with speed-trial information.
Chapter 6

(Figure 6.3). The speed-trial was activated by pressing one out of two pushbuttons, placed in front of the navigators. By pressing the ‘+’ button, PCE information was presented on the basis of increasing revolutions of the propeller shaft; pressing the ‘-’ button, PCE information was presented assuming decreased revolutions. The trial rpm-setting was presented in red on the rpm indicator. To avoid confusion with the actual rpm values, a red triangle would appear on the screen to warn the operator that the presented information did not correspond to the actual status. The speed-trial was ended by pressing the ‘+’ and ‘-’ buttons simultaneously.

Figure 6.3 The ARPA/PCE/course/speed navigation display. The basic ARPA display is supplemented with Predicted Capability Envelope (PCE) information based on variable propulsion of the controlled vessel. The red bar on the propulsion indicator (Revs) represents the rpm of the speed trial. A red triangle appears on the screen to remind the navigator that the speed trial function is active.
Experiment 5: Ship navigation with preview and capability prediction

Scenarios
The participant’s vessel started 3 nm from the centre line of the separation zone, with an nominal speed of 15 knots. Vessels approaching from port side were scheduled such that an initially close approach existed (Passenier, Van Breda & Kerstholt, 1997). This forced the participants to maintain their initial speed during the first part of the trial, so preventing them from quietly determining their strategy. In the high-workload task conditions, an additional CMT task was started during this part of the scenario. Vessels approaching from starboard side were scheduled in dynamic scenarios. During the experiment, the display types were presented to the participants in balanced order; the vessel traffic scenarios were randomized. All vessels followed the lanes and did not alter course. There was no wind and the current was 3 knots in the direction 90°.

Procedure
The participants contributed to the experiment for half a day. In an introductory session, the participants were familiarized with the manoeuvring simulator. This was followed by a 30 minutes practice trial for each individual display type. On the basis of pilot studies, it was determined that this amount of trials would be sufficient to obtain a stable performance level from each participant. If this was not the case, it was allowed to perform additional practice trials. Then, the experimental trials were started. These were presented in 3 blocks of 6 trials; each block representing a display type; each trial representing a different traffic scenario. To avoid order effects, display types and traffic scenarios were presented in balanced order. Each trial took 20 minutes.

Performance measurement
The state variables of position, heading, speed, rate of turn, and rudder deflection, autopilot set-point and propulsion set-point, were sampled and stored every 1 second. Performance was recorded in terms of navigation safety, operationalised as the violation of the minimum safety distance, the position error, and the average speed of the vessel. Only (priority) vessel traffic, approaching from starboard side, was considered in the data analysis. Safety distance violation was defined as the distance and time during which the participant’s vessel had been within 1.0 nm from any of the vessels. Distance was calculated as the Root-Mean-Square (RMS) distance error, expressed in m. The position error was defined as RMS deviation between the planned route and the actual sailed path, expressed in m. Speed was defined as the average speed of the vessel, expressed in knots. Finally, the autopilot and propulsion setting frequency was determined as a measure of control effort.
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Results

Violation of the minimum safety distance

Distance. All participants were able to perform the experimental trials. Two trials with the PCE/course/speed display type had to be aborted because one of the participants was confused about the way the speed trial facility was applied. A within-subject analysis of variance (ANOVA) on the violation distance, with display type (ARPA, ARPA/PCE/course, or ARPA/PCE/course/speed) and workload task condition (normal or high) as independent variables, showed a main effect of display type, $F(2,22)=3.77; p<.05$; explained variance 4.3%. This means that the distance violation differed for the three investigated display types. Figure 6.4 shows the mean distance violation as a function of display type and workload task condition, averaged over all participants.

![Graph showing distance violation](image)

**Figure 6.4** Distance violation (RMS distance error) as a function of display type and workload task condition, averaged across participants.

The main effect of display type on distance violation showed that the violation when the ARPA display type, the baseline condition, was used was larger than it was for both the ARPA/PCE display types. Note that these differed by a factor four. A post-hoc Tukey comparison test confirmed the finding that distance violation with the ARPA display type differed significantly from that with both the other display types ($p<.05$). No differ-
ence was found between the two PCE display types. No interaction was found between display type and workload task condition. Although Figure 6.4 suggests difference in task performance as function of workload with the ARPA/PCE/course/speed display type, no significant effect of workload was found.

*Time.* Figure 6.5 shows a histogram, depicting the mean period of time that the minimum safety distance of 1.0 nm was violated, averaged across participants. The horizontal axis is divided into intervals of 0.1 nm, starting 0.5 nm from the threat vessel and ending up at the minimum safety distance of 1.0 nm. It can be seen that with the baseline ARPA display type, a considerable amount of time was spent within the minimum safety distance of 1.0 nm. The Figure shows that the participants, in some instances, were as close as 0.5 nm distant from other traffic ships. With both the ARPA/PCE display types this was not the case; safety distance violations occurred mainly in the interval 0.9 to 1.0 nm distance. A Pearson Chi-square test indicated that the results with the baseline ARPA display type differed significantly from both the PCE display types, \( \chi^2(5) = 30.4; p < .001 \) and \( \chi^2(5) = 35.6; p < .001 \), respectively.

![Histograms](image)

Figure 6.5 Period of time that the minimum safety distance of 1 nm was violated as a function of display type, averaged across participants. The investigated display types were: (a) ARPA, (b) ARPA/PCE/course, (c) ARPA/course/speed.

*Position error*

An ANOVA on the position error, with display type (ARPA, ARPA/PCE/course, or ARPA/PCE/course/speed) and workload task condition (normal or high) as independent variables, showed no significant effect of any of the independent variables. The mean
position error with the standard ARPA display was 665 m, with the ARPA/PCE/course display this was 670 m, and with the ARPA/PCE/course/speed display 762 m. No significant effect of workload task condition was found. No interaction was found.

**Speed**

An ANOVA on the average speed showed no significant effect of any of the independent variables. The average speed was about 7.3 knots with each of the display types. Largest standard deviations were found when the ARPA/PCE/course/speed display type was used. No interaction was found.

**Control effort**

An ANOVA on the propulsion and autopilot (heading) setting frequencies showed no significant effect of any of the independent variables. The mean propulsion setting frequency was about 1.7 per trial for all display types. The range of mean autopilot setting frequency differed was 7.1 with the ARPA display, 6.1 with the ARPA/PCE/course display, and 6.0 with the ARPA/PCE/course/speed display. Because of the large standard deviations, no significant effect of workload task condition was found. No interaction was found.

**Discussion**

The potential benefits of PCE information for ship anticipation support were investigated in a simulator study, using a short term manoeuvre in which a busy traffic separation scheme was crossed with a 110,000 dwt vessel. The results of the experiment indicate that navigational performance was significantly improved when the participants used PCE information as an addition to a baseline ARPA radar display. The minimum safety distance to other traffic ships was violated less frequently and less seriously, by a factor of four on the average. PCE information enabled the navigators to better anticipate and assess critical traffic situations. Some differences in task performance between the two PCE display types were found. The PCE/course display type produced the most accurate navigation, but did not produce any differences due to workload task condition. Observations by the experimenter and self-observations by the participants revealed that the participants were not interested in slowing down their speed. Navigators prefer to plan their manoeuvres on the basis of a constant (maximum) speed. The participants therefore estimated speed loss to cause a long term slow down of the voyage, which they tried to avoid. The availability of a speed-trial facility was found to confuse the participants. The speed-trial facility produced an overall tendency to violate the minimum safety distance more seriously, particularly in
Experiment 5: *Ship navigation with preview and capability prediction*

high-workload task conditions; to further deviate from the planned route; and to slow down ship’s speed. Interestingly, it was found that fewer autopilot setpoint corrections were given when PCE information was available. This is in contradiction to the findings of the earlier experiments, in which more corrective rudder actions were found. In the current experiment navigators had more overview, using available safe areas to navigate. Note, however, that the PCE speed-trial facility should be further investigated.

**Conclusion**

Results of the experiment show that PCE in combination with preview and path prediction information effectively supports non-routine supervisory control performance (navigation functions). It appeared that almost no safety distance violations occurred, in contrast to conditions where standard ARPA information was provided. Navigators were able to select the proper alternative route, also in case an emergency occurred. The use of a speed-trial based PCE facility needs more investigation. Expectation 3 was confirmed.
Chapter 7

General discussion

Three expectations with respect to effective support of supervisory vehicle control functions were tested in five simulator experiments:

- Expectation 1: preview information supports routine supervisory control (guidance function) in slow tasks, i.e., where control is performed with less than maximum control effort.
- Expectation 2: preview and path prediction information support routine supervisory control (guidance function) in rapid tasks, i.e., where control is performed with near to maximum control effort.
- Expectation 3: preview and path prediction information, in combination with information presenting the predicted manoeuvring margins — the so-called predicted capability envelope of the controlled vehicle — support non-routine supervisory control (navigation function). These predicted manoeuvring margins enable selection of the safest route to proceed; preview and path prediction information enable safe guidance and control along this selected route.

The first expectation concerned the need of preview to obtain accurate control in (routine) guidance functions, in conditions where less than maximum control effort is required. It is characteristic for these conditions that sufficient time and space is available to correct tracking errors through feedback information. Since many studies in this respect are reported in the literature, this expectation was considered as a reference in this study. This expectation was confirmed by the results of Experiments 1 and 2 concerning aircraft control, where adequate preview information enabled pilots to assess their control performance and to correct tracking errors adequately. Supervisory control may then be considered as a visual control task, where performance primarily depends on the ability of the operator to perceive the planned route and to assess future position error relative to that route. In the current study, a fighter aircraft flight task was employed, where pilots used a spherical perspective display representation of the task environment for accurate preview.

The second expectation concerned the need of additional path prediction information in (routine) guidance functions, in conditions where near to maximum control effort is required. Operators need to anticipate in these conditions. This was tested in Experiment 3,
where combined preview and path prediction information was found to effectively support navigators while they controlled a ship along a planned route with course alterations of varying need of control effort. Generally spoken, operators first roughly preset their controls based on preview and rules-of-thumb for control, then perform corrective control actions based on error information from path prediction in a next phase of the manoeuvre.

It appeared, however, that task performance deteriorated considerably in the navigation function, when unexpected events occurred. This was tested in Experiment 4, where an unexpected (non-routine) passing manoeuvre had to be performed because the fairway was partly blocked. During non-routine manoeuvres, significant changes of the process state may be expected which are not presented by path prediction. Moreover, path prediction does not show the manoeuvring margins, representing the boundaries of safe operation. Such information is essential in helping the navigator to select the best solution for the actual problem situation.

The third expectation concerned the need of Predicted Capability Envelope (PCE) information to solve emergencies in (non-routine) navigation functions. Navigators have difficulties to anticipate in unexpected task conditions because incidents occur and no rules are available from previous experiences. PCE information shows the predicted manoeuvring margins of the vessel which represent the boundaries for safe operation. Results of Experiment 5 showed that navigators were able to solve problem situations by generating safe alternative routes for guidance when PCE information was provided. The route was properly re-planned, whereas the available preview and path prediction information allowed safe guidance along that re-planned route.

Navigators require information to support their limited anticipating capabilities in supervisory vehicle control functions. The findings in this study emphasize the need of three elements to be included in this information:

- preview, i.e., information that enables immediate perception of the planned route, and assessment of future position error relative to that route
- path prediction, i.e., information that represents the predicted track ahead
- capability prediction, i.e., information showing the predicted boundaries for safe operation of the controlled vehicle.

Preview and path prediction information supports the guidance function (rule-based behaviour); capability prediction information supports the navigation function (knowledge-based behaviour). Using these elements, accuracy of supervisory vehicle control will be enhanced, improving safety of navigation considerably in non-routine task conditions.
It is suggested that integrated prediction information could be of particular importance for the guidance and navigation of high-speed craft. Because continuous observation of the outside world and of the controlled process state is required, it is advised to show prediction information as an overlay, superimposed over the external world scene, thus indicating where safe areas of navigation are located.

The present study focussed on anticipation behaviour in guidance and control functions with a limited time horizon. Generally spoken, the time horizon of these functions is relatively short, for example, 5 to 10 times the time constant of the controlled process. Many navigation functions exist that encompass larger time horizons, e.g., weather routing, tidal slots, availability of pilots, local berthing rules. In that case, more factors affect the controlled variables, requiring more knowledge based support. More research is needed to assess these longer term processes more objectively.

It is recommended to improve technology for prediction. An extrapolator is relatively simple to implement because extrapolators operate on the basis of a limited quantity of sampled data. In practice, however, it is questionable whether sensors are capable to provide signals with sufficient stability and accuracy.
Summary

Anticipating behaviour in supervisory vehicle control

Leo van Breda

Vehicle control may be considered as a hierarchically structured set of functions. Plan conception and plan selection activities are performed in the navigation function, verification and adjustment of the short-term voyage progress are performed in the guidance function, and typical closed-loop control activities are performed in the control function. Supervisory control of vehicles deals with automated vehicle control functions to a large extent. Nowadays, technology permits the typical control functions to be entirely executed by automated systems, while the navigation and guidance functions are still partially automated. The operator, who may observe the controlled process directly, acts as a manager who supervises the system and only interacts with the automated system by performing corrective actions. The human operator remains the primary responsible factor, specifying the constraints, and procedures in terms of setpoint changes for the automated system. It is known, however, that humans have certain limitations in supervising capabilities, particularly when slowly responding systems are concerned. Humans are not always able to anticipate, that is, to mentally predict future state information by applying knowledge of the goals, process characteristics and disturbances that act on the system, considering the current control actions and the observed changes in process state.

Literature on human performance models indicates that accurate vehicle control mainly depends on the operator's knowledge of the controlled process characteristics and the route to be followed, on the ability to predict the future states of the controlled process, and on the quality of track planning and track following activities. A technical system to support operator anticipating behaviour should provide information that addresses these elements. The current study focusses on the question what type of information is required to obtain accurate supervisory vehicle control.

Five experiments were conducted in a man-in-the-loop simulator facility, where participating subjects were required to perform specific aircraft and ship control tasks, in routine and in non-routine task conditions, using different information systems. Task performance was
measured and analysed with respect to accuracy of guidance and quality of navigation. The need of three information elements for accurate supervisory control was investigated:

- preview information that enables immediate perception of the planned route, and assessment of future position error relative to that route
- path prediction information, showing the predicted track ahead
- capability prediction information, showing the predicted consequences of a range of process control actions with respect to the process states reaching their predetermined safety margins, thus indicating the boundaries of safe operation.

The results of the experiments indicate that accurate supervisory vehicle control is obtained when information is provided containing the following complementary elements:

- Capability prediction information, needed to support the navigator in the navigation function (knowledge-based behaviour), where non-routine task conditions occur. Capability prediction aids the mental process of generating alternative solutions for a problem situation. These alternatives are presented as an advise to the navigator. Knowledge of the safety margins allows navigators to properly re-plan the route by selecting the safest alternative.
- Preview and path prediction information, needed to support accurate guidance along that alternative route (rule-based behaviour). During guidance, only routine task conditions exist. Navigators first roughly pre-set their controls based on preview and rules-of-thumb for control, then perform corrective setpoint control actions based on error information provided by the path predictor.

It is suggested to apply the findings of this study for the guidance and navigation of high-speed craft. Because continuous observation of the outside world and of the controlled process state is required, it is advised to show prediction information as an overlay, superimposed over the external world scene, thus indicating where safe areas of navigation are located.

The present study focussed on anticipation behaviour in guidance and control functions with a limited time horizon, for example, 5 to 10 times the time constant of the controlled process. Many navigation functions exist that encompass larger time horizons. In that case, more factors affect the controlled variables, requiring more knowledge based support. Additional research is needed to assess these longer term support systems more objectively.

It is recommended to improve technology for prediction. For example, an extrapolator is relatively simple to implement because extrapolators operate on the basis of a limited quantity of sampled data. In practice, however, it is questionable whether sensors are capable to provide signals with sufficient stability and accuracy.
Samenvatting

Anticiperend gedrag bij voertuig supervisietaken

Leo van Breda

Het besturen van een voertuig kan worden opgevat als het uitvoeren van een hiërarchisch geordende set van functies. In de navigatiefunctie wordt het reisplan samengesteld en bijgesteld tijdens de reisuitvoering, in de uitvoeringsfunctie wordt de voortgang van de reisuitvoering geverifieerd en gecorrigeerd, in de regelfunctie worden de specifieke stuurregelacties uitgevoerd. Bij het besturen van voertuigen onder supervisory control zijn de besturingsfuncties geheel of gedeeltelijk geautomatiseerd. De huidige stand van de techniek laat toe dat specifieke regelfuncties volledig zijn geautomatiseerd; voor de navigatie- en reisuitvoering-functies is dat slechts gedeeltelijk het geval. Bij supervisory control is de operator een manager die systemen superviseert en alleen acties uitvoert via automaten. De operator is steeds de primair verantwoordelijke en bepaalt de randvoorwaarden en de te volgen procedures voor het bedienen van de automaten. Het is evenwel bekend dat de mens beschikt over beperkte supervisie-capaciteiten, vooral wanneer het gaat om langzame processen. De mens is niet altijd in staat goed te anticiperen, dat wil zeggen, hij of zij is niet altijd in staat de toekomstige toestand van een dynamisch proces nauwkeurig te voorspellen op basis van het beoogde doel en de aanwezige kennis van het te regelen proces en de verstoringen, en op basis van momentane stuuracties en waargenomen verandering van het proces.

Literatuur over modellen van menselijk functioneren geeft aan dat nauwkeurig stuurgedrag voornamelijk wordt bepaald door aanwezige kennis van proces eigenschappen en geplande route, door de mate waarin het gedrag van toestandsvariabelen kan worden voorspeld, en door de kwaliteit van route plannen en route volgen. Een systeem dat operator anticipatie ondersteunt bij de taakuitvoering in supervisory control zou daarover informatie moeten verschaffen. Deze studie richt zich op de vraag welke informatie noodzakelijk is voor nauwkeurig stuurgedrag bij supervisory control van voertuigen.

In een vlieg- en vaar-simulator werden vijf experimenten uitgevoerd. Proefpersonen werden opgedragen specifieke voertuig besturingstaken uit te voeren, onder vertrouwde en niet-vertrouwde (onverwachte) omstandigheden, met verschillende informatiesystemen ter onder-
Samenvatting

steuning van de taakuitvoering. Taakprestatie werd gemeten en gecentraliseerd met betrekking tot nauwkeurigheid en kwaliteit waarmee de navigatie- en reisuitvoeringsfuncties werden uitgevoerd. De noodzaak van drie elementen voor het verkrijgen van nauwkeurig stuurgedrag werd onderzocht:

- preview; informatie waaruit de geplande route, en de toekomstige afwijking van die route, snel kunnen worden afgeleid
- path prediction; informatie over de voorspelde baan van het voertuig
- capability prediction; informatie die aangeeft wat het voorspelde effect is van een reeks stuuracties met betrekking tot het overschrijden van vastgestelde veiligheids marges. Deze informatie geeft aan in hoeverre veilige taakuitvoering nog mogelijk is.

De resultaten van experimenten geven aan dat nauwkeurig stuurgedrag bij supervisory control van voertuigen wordt verkregen wanneer informatie is samengesteld uit de volgende elkaar aanvullende elementen:

- Capability prediction, nodig voor het ondersteunen van operators in de navigatiefunctie (kennis-gebaseerd gedrag) in niet-vertrouwde omstandigheden. Capability prediction helpt bij het genereren van oplossingsvarianten voor een bepaald probleem. De varianten worden als een advies aan de navigator gepresenteerd. Mede op basis van de getoonde veiligheids marges kan dan de meest veilige nieuwe route worden gekozen.
- Preview en path prediction, nodig voor het ondersteunen van operators bij het nauwkeurig volgen van de gekozen route (regel-gebaseerd gedrag). Het gaat daarbij om de taakuitvoering in vertrouwde omstandigheden. De navigator voert eerst een globale voorinstelling uit met zijn besturingsmiddel, op basis van preview en op basis van eigen vuistregels, en corrigeert daarna eventuele afwijkingen op basis van informatie over de voorspelde baan.

De resultaten van deze studie kunnen worden toegepast bij het varen met hoge snelheid scheep. Deze schepen vereisen continue uittuik vanaf de brug, en continue informatie over de toestand van het schip. Predictie informatie zou in dat geval gepresenteerd kunnen worden als een overlay, dat wil zeggen, geprojecteerd op het buitenbeeld. Een dergelijk informatie systeem geeft dan aan welke de gebieden zijn voor veilig manoeuvreren.

De hier gepresenteerde studie is gericht op anticiperend gedrag in functies met beperkte tijdsduur, bijvoorbeeld 5 tot 10 keer de tijdconstante van het geregeld proces. Veel navigatiefuncties hebben echter betrekking op langere termijn processen. In dat geval zijn er veel andere factoren dan in deze studie beschouwd die het proces beïnvloeden. Mede gebruik van kennisystemen is dan vereist. Voor het objectief beoordelen van langere termijn ondersteuning is verder onderzoek vereist.

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Aanbevolen wordt de technologie voor predictie te verbeteren. Bijvoorbeeld, een extrapolator is eenvoudig te implementeren en functioneert op basis van een beperkte hoeveelheid gegevens. In de praktijk is het de vraag of er wel sensoren bestaan die deze gegevens leveren met voldoende nauwkeurigheid en stabiliteit.
References


References


References


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References


References


Rasmussen, J. (1983). Skills, rules, and knowledge; signals, signs, and symbols, and other
distinctions in human performance models. *IEEE Transactions on Systems, Man,
and Cybernetics, 13*, 257-266.

Rasmussen, J. (1986). *Information processing and human-machine interaction: An ap-


Roscoe, S.N. & Williges, R.C. (1975). Motion relationships in aircraft attitude and guid-


Factors, 23* (3), 341-353.


IL: Human Kinematics.


The Netherlands: TNO Institute for Perception.

the navigation performance and mental workload of the Officer of the Watch. *The


Amsterdam, The Netherlands: National Aerospace Laboratory.

(PCCADS). *Proceedings AGARD-D-425: The man-machine interface in tactical

Factors in Electronics, 7*, 91-102.

Sheridan, T.B. (1970). On how often the supervisor should sample. *IEEE Transactions on

Sheridan, T.B. (1980). *Computer control and human alienation* (Technology Review,


References


Curriculum vitae

Leo van Breda was born in Hoevelaken, on 2 August 1946. After having received his HBS-B diploma at the "Rijks Hogere Burgerschool Amersfoort" in 1964, he studied Electrical Engineering at the "Gemeentelijke Hogere Technische School Utrecht". In 1968 he obtained his B.Sc. degree. From 1968 to 1971 he participated in research projects for Honeywell-Bull on the design of high-speed computer peripherals in Paris and Belfort, France. In May 1971 he joined TNO Human Factors Research Institute in Soesterberg, the Netherlands. He participated in human factors studies for the Netherlands Foundation for Maritime Research on the potential benefits of ship bridge automation, and for the Netherlands Ministry of Transport and Public Works on the design of waterway lay-out. During a sabbatical leave at the Defence and Civil Institute for Environmental Medicine (DCIEM) in Toronto, Canada, 1980-1981, he further specialised in the use of analysis techniques for human-machine interface design, with the emphasis on network modelling techniques to predict total system performance. Since 1990, his main research activities concern vehicle control and tele-operation studies.