# Effect of Path Prediction on Navigational Performance

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A simulator experiment was conducted to determine the potential benefits of path prediction on the navigational performance of channel-bound vessels. Channel pilots had to sail an approach channel under critical conditions in a deep-draught vessel. For the navigation task, basic radar information was used, supplemented by three different path predictors. Predictor (a) was based on an accurate fast-time hydrodynamic model of the vessel and showed the exact future path of the vessel. Both other path predictors were less accurate, relatively simple extrapolators; predictor (b) was based on a speed and rate of turn extrapolator and showed a curved representation of the future path; predictor (c) was based on a linear speed and course extrapolator and showed the ground velocity vector. Navigational performance was determined in terms of deviation from the planned route. The results indicate that the relatively simple extrapolator (b) supported the navigational task as effectively as the highly accurate path predictor (a). In comparison with the linear extrapolator (c), the navigational accuracy increased by a factor of two. It is concluded that support in anticipating the vessel's rate of turn is essential for accurate navigation. Implications of the use of path prediction for ship control are discussed.

1. INTRODUCTION. Sailing an approach channel in a deep-draught vessel 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 with the typical manoeuvring characteristics of such a vessel. Since visual navigation is no longer sufficient to guarantee safe passage through a channel, pilots actually use an electronic harbour approach system. At Europort Entrance, Hook of Holland, the system used 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 position fixing is limited and the stability tends to fluctuate considerably. New technological developments in the field of satellite navigation systems and geographical information systems offer possibilities to replace 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. In this human factors study, the question is addressed as to whether path prediction would further increase the navigational performance, so that implementation of a path predictor function in the design of a new BB may be considered.

A path predictor is a computer-based system that shows the ship's future path on a display. Exploratory studies revealed that human control of slow responding systems may be improved by means of predictive information. Path prediction based on extrapolation has been investigated (Bernotat and Witlok, 1965; Berlekom, 1977); Kelley, 1978; McLane and Wolf, 1967 showed positive effects of path prediction on navigational accuracy and on the learning ability of ship control tasks. Also Pew, 1966; Bertsche and Cooper, 1979; Hayes, 1979 argued that path prediction based on speed vectors could enhance navigational performance. A more recent study was performed in 1990 (Van Breda, Passenier and Schuffel). In this study, the navigational performance with an adaptive path predictor; that is, a path predictor that continuously adapts the predictive model parameters according to changing navigational conditions (Passenier, 1989), was compared with conventional navigation methods – that is, parallel-indexing (Spaans, 1979) and ground velocity vector (Sheridan, 1966). The results indicated that adaptive path prediction improved ship control accuracy considerably. In particular, when large course changes had to be performed, the deviation from the planned route was reduced by nearly 70 percent, resulting in an average absolute deviation of 50 metres. Although these studies pointed out in a quantitative way that path predictors do improve control performance of ships, application did not follow. Presumably, inaccuracy of predictor functioning and difficulties in operation as well as the requirements for interfacing with navigation systems on board the vessel were the main reasons. It is not obvious that all parameters needed for accurate path prediction can easily be derived from equipment installed on the ship's bridge. This has consequences for the accuracy of the applied path predictor. It is understood that path predictors for pilotage support on board channel-bound vessels should be designed for portable application, without any need of interfacing. Path predictors can be classified according to the type of mathematical predictive model that is incorporated:

(i) *path prediction based on an accurate hydrodynamic model*. The future path is determined by fast-time iterations of an accurate hydrodynamic model of the vessel. The model inputs the actual state of the vessel and calculates the influence of disturbances (wind and current) on the vessel's manoeuvring behaviour (Inoue *et al*., 1981). Such a model is specific, since its parameters have to be identified and estimated for each individual ship. This is the main reason that path predictors of this type are not used in practical situations. Application may be valid in training simulators when effects of control actions must be shown to students;

(ii) *path prediction based on an adaptive model*. Path prediction is based on a relatively simple mathematical model which continuously adapts its parameters to the changing navigational conditions due to current, wind and water depth below keel (Van Amerongen, 1982; Passenier, 1989). A suitable method for on-line identification and adaptation to disturbances of the prediction-model parameters was determined by a structural comparison of different, well-known, identification schemes, and resulted in the application of extended-Kalman filtering techniques. This provided accurate path prediction, but to operate such a system on board a ship requires extensive interfacing with the on-board navigation systems;

(iii) *path prediction based on a static model*. Path prediction is based on a simple model describing a static relationship between the ship's turning radius, speed and rate of turn (van Roon, 1988). With such a model, the wheel-over-point is determined as a function of the ship's dimensions, inertia and water current. Since such a model includes many rules of thumb, the accuracy of the model output is limited. From the user's point of view, no specific knowledge of the ship's manoeuvring behaviour is required, and no interface with the on-board systems is required to operate the predictor;

(iv) *path prediction based on extrapolation*. The ship's future path is determined by extrapolation of the actual values of the vessel's state variables. Such an extrapolation model assumes that these state variables remain the same in the near future (Heikkilä, 1993). A path predictor of this type may be simple (extrapolation of first order components, e.g. speed), or more complex (extrapolation of first and second order components, e.g. speed and accelerations).

The above list suggests that, the higher the accuracy of the path predictor, the more input the predictive model needs; that is, actual values of the vessel's model parameters and state variables. However, the path predictor evaluated in this study is foreseen for portable application, which implies that interfacing with on-board systems must be avoided as much as possible. Path prediction based on extrapolation seems to be a suitable solution. It is questionable, however, to what extent the limited accuracy of these extrapolators supports the pilot's navigation task.

The navigator intends to follow a planned route accurately. He anticipates the future deviation between the planned route and the estimated path of the ship. The planned route is derived from voyage planning and is marked on the chart or radar display; the estimated path is derived by extrapolating the perceived change in position and orientation of the vessel. This so-called perceptual anticipation can be supplemented by expectations about the future path of the ship based on knowledge of the vessel's dynamic behaviour, called cognitive anticipation (Poulton, 1974). Control based on cognitive anticipation makes the navigator select a rudder angle as a function of the actual conditions and the planned track. The navigator 'knows' the effect of his action, so he instantaneously anticipates the future deviation between the planned track and the estimated path. Control based on perceptual anticipation makes the navigator perform repetitive rudder corrections, since the estimated path is derived from extrapolation of the actual (variable) state and movement of the vessel. Control based on perceptual anticipation argument (Schuffel, 1986) leads to accurate navigation, provided that adequate time is available for the navigator to perceive the effects of his actions and to perform corrective measures (control by feedback). The less time there is available to perform the task, the more control based on cognitive anticipation is required. Experiments revealed that this may decrease the navigational performance considerably. Since a path predictor supports cognitive anticipation, it could be important to support critical manoeuvring tasks with a path predictor, for example, when large course changes must be performed under time pressure. The present study was carried out to investigate the extent to which various types of path prediction support the channel-navigation task. Under normal circumstances, the pilot is well aware of the navigational circumstances – the vessel's characteristics, the hydrological and meteorological conditions (Van der Ent, 1991) – whereas additional tables and rules of thumb are used to determine rudder actions at the wheel-over-point. It is questionable, however, whether this is sufficient in non-standard situations, for instance during unexpected changes in the vessel traffic, or when a passing manoeuvre must be performed if the channel is accidentally blocked (van Room, 1988).

The current paper describes a simulator experiment in which channel pilots were required accurately to perform a sudden passing manoeuvre with a deep-draught vessel. The ship's bridge was equipped with standard navigation instruments, supplemented by three different path predictors:

(i) '*Speed-rotation-inertia path predictor*'. Path prediction was obtained by fast-time iterations of the hydrodynamic model of the vessel. Since this model incorporated a complete mathematical description of the vessel's dynamic behaviour, inertia and influence of wind and current, an exact prediction of the vessel's future path was obtained, with the assumption that rudder angle and navigational circumstances remained the same.

(ii) '*Speed-rotation extrapolator*'. Path prediction was obtained by extrapolating actual speed and rate of turn of the vessel. This extrapolator did not incorporate the vessel's inertia, it assumed that speed and rate of turn of the vessel remained the same, as well as the effects of wind and current. Compared to path prediction type (i), this was less accurate, in particular for long-term predictions.

(iii) '*Speed extrapolator*'. Path prediction was obtained by linear extrapolation of the vessel's actual ground velocity vector. This is a standard provision in modern ARPA radar systems. Navigating with this path predictor was considered as the reference condition.

It is expected that path prediction will enhance the navigational performance. First, this was predicted by results of a former experiment in which navigators had to perform identical manoeuvres using an adaptive path predictor (Van Breda *et al.*, 1990). The results of this experiment indicated that path prediction particularly supported cognitive anticipation of the navigator, which is most needed in situations when large course changes have to be performed. Furthermore, it was expected that the navigation task would be best supported by a highly accurate path predictor, type (*a*). In contrast to this, it was expected that navigational support would be far less effective when a linear extrapolator was used, path predictor (*c*). This path predictor supports the perceptual anticipation of the navigator. The case where rate of turn was incorporated into the extrapolator – predictor (*b*) may be considered as an extension of predictor (*c*): additional support of the perceptual anticipation was provided. It was therefore expected that the navigational performance with predictor (*b*) would be somewhere in between the navigational performance with predictors (*a*) and (*c*). 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 pilot's navigation task. Pilot's performance was measured in terms of navigational accuracy, defined as deviation from the planned route. For the analysis, rudder control actions and the vessel's state variables were recorded.

## 2. METHOD

2.1. *Participants*. Six channel pilots participated in the experiment. They were all experienced pilots in the Euro- and IJ-Channel. Their ages ranged from 43 to 53 years, their experience as a pilot from 14 to 24 years.

2.2. *Task*. The participants had to sail a deep draught vessel (280000 dwt) accurately with a nominal speed of 7 knots along a predetermined route. Standard navigation information was available; that is, ARPA radar, meteorological and hydrological data. The intended route was presented on the radar screen, as well as the vessel's predicted path. Each trial started with the vessel following an initial straight route of 500 metres, whereas the course to steer was compensated for wind and current. This allowed the participant to observe the instruments and the outside scene. Then, a passing manoeuvre had to be performed when approaching the first pair of buoys (see Fig. 1). It was emphasised that the vessel had to be controlled as accurately as possible in between both pairs of buoys, as was indicated by the intended route. The course change for the passing manoeuvre varied from 10, 20, 30, 35 or 40 degrees, to port or starboard. There was no wind, the current was 2·5 knots, in direction 45, 135 or 270 degrees. The trial ended 250 metres after passing the second pair of buoys. The vessel could only be controlled by helmsman's orders: no propulsion orders were allowed.

2.3. *Apparatus*. The experiment was carried out in the TNO ship manoeuvring simulator. This simulator consisted of an image generator with projection system, a mock-up of an instrumented ship's bridge, and computer systems with an hydrodynamic model of the vessel. The image generator was a three-channel Evans & Sutherland ESIG2000 high-speed graphics processor, providing synthetic video scenes for the simulator vision system. This processor generated multiple channel, high resolution, video images; that is, 1500 to 2000 textured polygons and 800 × 600 pixel resolution per channel. The image update frequency was 30 Hz. For three channels, the viewing angle was 156° horizontal and 42° vertical. The images were presented in a Seos PRODAS HiView S-600 video dome. The viewing distance was about 3 metres. The mock-up 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 in relative motion, North-up (Fig. 2). The planned route was presented by straight solid lines, connecting waypoints. Along the right-hand screen edge, a menu for display interaction was presented, showing 'soft' push buttons for the radar display setting, and indicators for ARPA information presentation: own ship's heading and speed, target range and bearing, speed and course, passing distance and time. A variable range marker and parallel-index lines could be selected and manipulated. At the screen centre, the predicted path was presented, starting in the own ship's centre

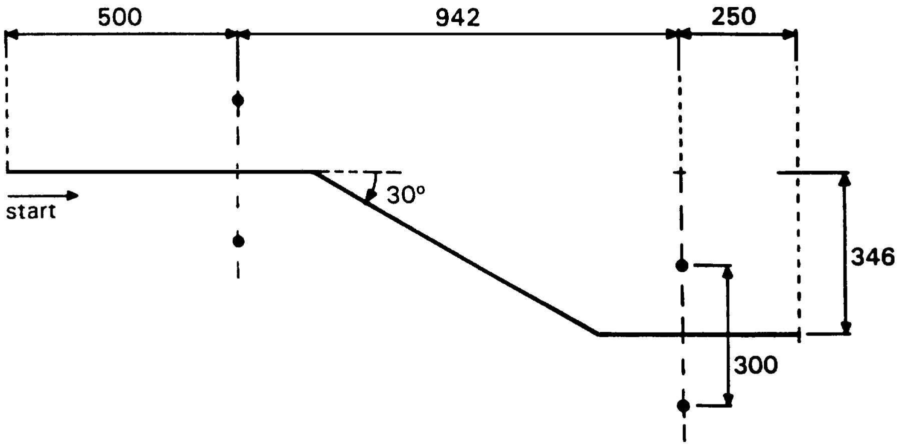
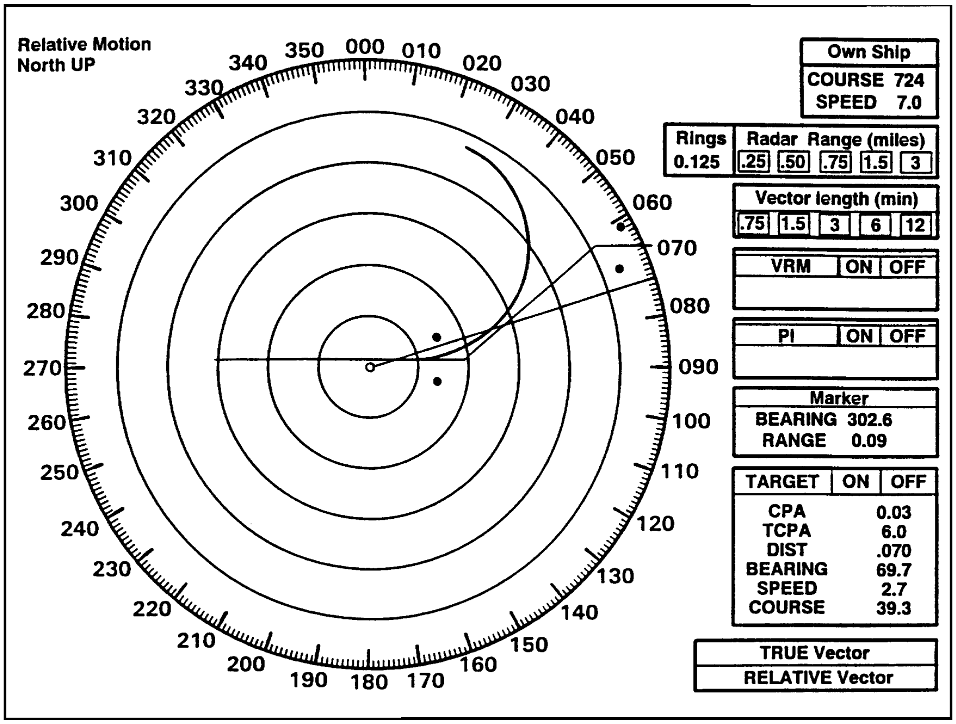


Fig. 1. A passing (double course change) manoeuvre of 30° to starboard. Beginning and end of the manoeuvre were marked by buoys. Measures in metres.



Own Ship
COURSE 724
SPEED 7.0

Rings 0.125

Radar Range (miles) .25 .50 .75 1.5 3

Vector length (min) .75 1.5 3 6 12

Marker
BEARING 302.6
RANGE 0.09

| | |
|---|---|
| CPA | 0.03 |
| TCPA | 6.0 |
| DIST | .070 |
| BEARING | 69.7 |
| SPEED | 2.7 |
| COURSE | 39.3 |

Fig. 2. The ARPA radar screen with path predictor. On the right hand screen edge, the interactive menu was shown. The curved solid line in the screen centre represents the 10-minute path predictor.

of gravity. The prediction time was 10 minutes; that is, the line represented the predicted path during the next 10 minutes. The status display showed the vessel's state variables: actual time of day, ship's heading, rate of turn, rudder angle, forward speed, rpm of the propeller shaft, and absolute wind and current data.

An intercom system was installed for rudder orders to the helmsman. The participants were told not to use the engine telegraph system. The setting of the propulsion system remained the same during the experiment. The hydrodynamic model of the vessel was based on data of a full-scale validation test with a 280000 dwt tanker *Esso Osaka* (Abkowitz, 1980). For this experiment, the model was a simplified multi-variable model (De Keizer, 1977) with which relevant nonlinear effects could be reproduced. Details of the model are listed in the Appendix.

2.4. *Path predictors.*

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

(ii) 'Speed-rotation extrapolator'. The predicted path was presented as a circular line. This path predictor extrapolated the actual forward speed and rate of turn of the vessel and did not include the vessel's inertia. Therefore, changes in rudder angle caused the predicted path to change slowly. The radius of the predicted path changed as long as the rate of turn of the vessel varied. Note that higher order effects were not included. For instance, a manoeuvre with decreasing rate of turn showed a circular-shaped predicted path; a predicted path to port never merged into a predicted path to starboard.

(iii) The 'speed extrapolator'. The predicted path was presented as the ground velocity vector.

2.5. *Procedure.* The experiment took a single day for each participant. In an introductory session, the principle of the simulator was explained, followed by a series of three 30-minute practice trials for familiarisation with each path predictor. In this session, the order was (*c*), (*b*), (*a*), which means that the participants started in the reference condition. The experimental trials were presented in three blocks of five. Each block represented a path predictor condition, and each trial a different course change for the passing manoeuvre. To avoid order effects, the conditions were presented in balanced order. Each time a new block was started, an additional practice trial was performed to avoid confusion. Each trial lasted for about 15 minutes. The vessel's state variables – that is, position, heading, speed, rate of turn and rudder angle – were sampled and stored at 1-second intervals. Performance was recorded in terms of position and direction error. The position error was defined as the root mean square deviation between the actual sailed path and the planned route, half-way through the passing manoeuvre and at the end, expressed in metres. The direction error was defined as the root mean square deviation between the direction of the actual ship's path and the planned route, half-way through the passing manoeuvre and at the end, expressed in degrees. Both measures were taken along route segments with a length of 200 metres.

## 3. RESULTS

3.1. *Position error*. A within-subject analysis of variance applied to path predictor (PP = type (*a*), (*b*) or (*c*)) and course change of the passing manoeuvre (CC = 10, 20, 30, 35 and 40°) showed a main effect of display type and course change, $F(2, 10) = 12{\cdot}0$; $P < 0{\cdot}01$ and $F(4, 20) = 3{\cdot}8$; $P < 0{\cdot}05$ respectively. This result indicates that the position error was different for the various types of path predictor and for the course changes.

The main effect of path predictor on the position error revealed that smallest position errors were obtained with PP (*a*) and (*b*), the largest with PP (*c*). The mean position error with PP (*a*) and (*b*) was about 35 metres, with PP (*c*) this was about 75 metres. Best performance was achieved with PP (*a*): the mean position error was nearly reduced by 65 percent compared to PP (*c*). A Tukey *post hoc* comparison test indicated that the position error with PP (*c*) differed significantly from both other PP types. No differences was found between position errors with path predictor (*a*) and (*b*).

The main effect of course change on position error was as expected: the position error increased with larger course changes, being 30 metres at 30 degrees and about 60 metres at 40 degrees. No interaction was found between PP and CC, although there was a tendency that the difference between PP would

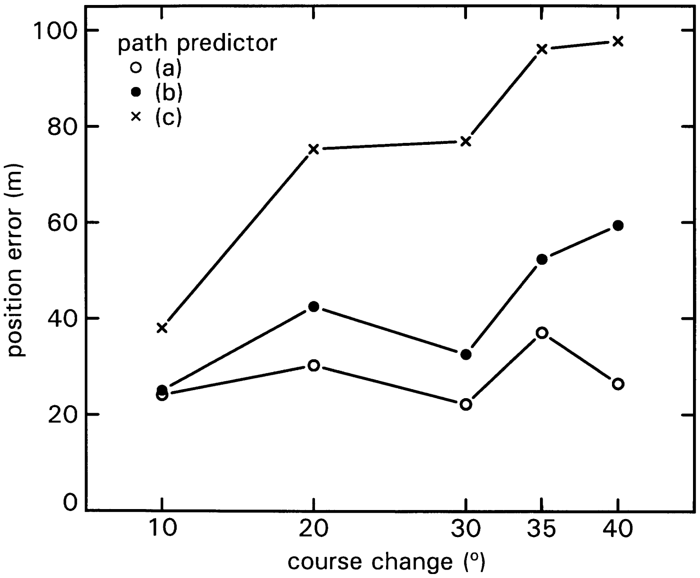


Fig. 3. Position error as function of path predictor (PP) and course change of the passing manoeuvre (CC), averaged over participants. (*a*), 'speed-rotation-inertia path predictor'; (*b*), 'speed-rotation-extrapolator'; (*c*), 'speed-extrapolator'.

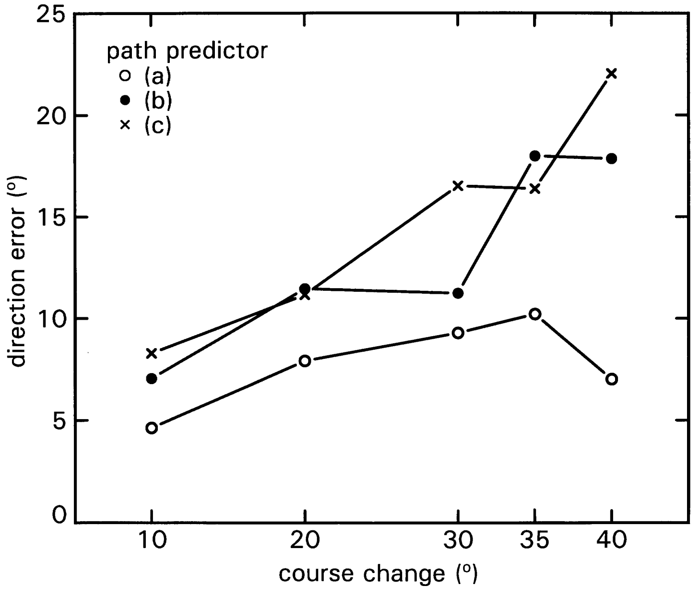


Fig. 4. Direction error as function of path predictor (PP) and course change (CC), averaged over participants. (*a*), 'speed-rotation-inertia path predictor'; (*b*), 'speed-rotation-extrapolator'; (*c*), 'speed-extrapolator'.

increase when larger CCs were performed. Figure 3 shows that smallest deviations occurred with PP (*a*) and (*b*).

3.2. *Direction error*. An analysis of variance applied to path predictor (PP = (*a*), (*b*) or (*c*)) and course change of the passing manoeuvre (CC = 10, 20, 30, 35 and 40 degrees) showed a main effect of path predictor and course change, $F(2, 10) = 9{\cdot}5$; $P < 0{\cdot}01$ and $F(4, 20) = 6{\cdot}0$; $P < 0{\cdot}01$ respectively.

The main effect of path predictor on the direction error indicated that the direction error was considerably larger with PP (*b*) and (*c*), compared to PP (*a*): on average 15° *vs.* 8°, respectively. The direction error was reduced by a factor two when PP (*a*) was used. A Tukey *post hoc* test indicated that the direction error with PP (*a*) differed from PP (*b*) and (*c*).

The main effect of course change on the direction error corresponded largely with the main effect on position error. The direction error with small CC was limited (about 7°), increasing with larger values of CC (about 17°). No interaction was found, although there was a tendency that the direction error increased with larger course changes when PP (*b*) and (*c*) were used, compared with PP (*a*). Figure 4 points out that the direction error remained more or less the same when PP (*a*) was used; about 8°.

4. DISCUSSION. The results of the experiment indicated that the best navigational performance was obtained with a path predictor based on a predictive model that incorporated at least *forward speed and rate of turn* information of the vessel, as was the case with path predictors (*a*) and (*b*). The deviation from the planned route was then on average about 35 metres, a

reduction of 50 percent compared to the speed extrapolator in the reference condition; that is, the ground velocity vector of the path predictor (*c*). Note that in the present experiment the performance with path predictors (*a*) and (*b*) was not completely identical: a significant direction error was found with path predictor (*b*). This suggests that there was a less 'smooth' passage when path predictor (*b*) was used.

No effect of path prediction was found in conditions with small course changes – that is, course changes up to 10° or 15°. Pilots were able accurately to follow the intended route: the perceived movements of the vessel provided adequate feedback to the navigator (perceptual anticipation), minimising the need for additional support. Larger course changes, however, caused the navigational performance to degrade considerably, which indicated that additional, mainly cognitive support, was needed. Most accurate navigation was obtained with path predictor (*a*), a predictor that supported cognitive anticipation. However, the participating pilots also performed very well with path predictor (*b*), a predictor that mainly supported perceptual anticipation. The navigational performance with predictor (*b*) was even comparable to the highly accurate path predictor (*a*). Apparently, combined extrapolation of speed and rate of turn information enabled effective anticipation during course change manoeuvres. In this respect, Jensen (1981) and Roscoe *et al.* (1981) found comparable results in aircraft control. They argued that predictive displays based on speed information only provided little help in following a curved path because they only indicate a straight-ahead projection of the vehicle's present path. Speed information was estimated to be only useful as an indicator for the drift, helping to reduce lateral steering error in circumstances with cross-disturbances, particularly along straight segments of the route; adding turn-rate information improved the steering performance along a curve route. However, no comparable quantitative results were available on this matter.

Since it was found that the navigational accuracy had a tendency to decrease during larger course changes, even with path predictor (*a*), it can be concluded that it is still possible to improve task performance. Results of an earlier experiment (Van Breda *et al.* 1990) indicated that the navigational accuracy remained at a more or less constant high level when the navigator was able to perform 'predictive trials', enabling him or her to explore the manoeuvring margins. In the present experiment, the predicted path was depicted as a single line on the display, representing the ship's future path assuming that the vessel's actual state remained the same. This hinders optimal judgement of the vessel's manoeuvring capabilities, in particular when counter rudder actions are performed. Considerable changes in the system's state may then be expected. Effects of these changes are not considered by the path predictors in the current experiment. It is therefore advised to investigate the benefit of additional provisions, for example, 'predictive trials' (Passenier, 1989) or presentation of 'manoeuvring margins', thus providing more insight in the capabilities and limitations of the ship system.

The analysis 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 controlling large vessels along a predetermined route. He knows the manoeuvring characteristics of the vessel and uses additional navigation tables and simplified (rules of thumb) formulas to determine the wheel-over-point. In the present experiment, however, it was agreed to perform more or less unexpected scenarios. For the pilot, there was not enough time available to consult tables or to perform calculations, which hampered the navigation task.

For the implementation of a path predictor it was stated that minimum interfacing is required with the vessel's on-board navigation system. This is particularly important when path predictors are applied in a portable harbour approach system. In this respect, extrapolators are favourable since they operate on the basis of limited sampled data.

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## APPENDIX

*Hydrodynamic model ‘Esso Osaka’*. The hydrodynamic model of the manoeuvring characteristics of the ‘*Esso Osaka*’ consists of a set of multi-variable equations (De Keizer, 1977) describing the relation between rudder angle and forward speed cq. rate of turn of the vessel. The model includes the most important nonlinear effects, characterizing the dynamic behaviour of vessels during large rudder angles. A summary of the model is presented below:

$$r^* = \frac{L}{u}\frac{\partial \psi}{\partial t}, \tag{1}$$

$$u^* = \frac{\Delta U}{U_0}. \tag{2}$$

Variable $r^*$ is the normalised rate of turn, $L$ the length of the vessel, $u$ the forward speed, $U_0$ the cruising speed, $\psi$ the heading, and $u^*$ the relative loss of forward speed due to rate of turn. The relationship between these variables and the rudder angle can be expressed in a set of first order differential equations

$$\tau^* \frac{L}{u}\frac{\partial r}{\partial t} + \frac{u}{L} H(r^*) = K^* \frac{u}{L}\delta, \tag{3}$$

$$\tau_u^* \frac{L}{u}\frac{\partial u^*}{\partial t} + H_u(u^*) = K_u^* \, r^{*2}, \tag{4}$$

$$v = -\gamma^* L \, r, \tag{5}$$

in which $v$ is the drift, $\gamma^*$ a constant and $\delta$ the actual rudder angle. With the normalised time constants $\tau^*$ and $\tau_u^*$ and with the gain factor $K^*$ and $K_u^*$, the manoeuvring behaviour and speed reduction due to rate of turn can be calculated, given the specific ship's parameters. The nonlinear feedback parameters $H(r^*)$ and $H(u^*)$ are defined as

$$H(r^*) = \alpha_1 \, r^{*3} + r^*, \tag{6}$$

$$H_u(u^*) = \alpha_2 \, u^{*3} + u^*. \tag{7}$$

Parameters $\alpha_1$ and $\alpha_2$ are constants. The speed components of the vessel can be calculated, with $U_{cx}$ and $U_{cy}$ as components that describe water current in x and y direction.

$$u_x(t) = u(t)\cos\psi(t) - v(t)\sin\psi(t) + U_{cx}, \tag{8}$$

$$u_y(t) = u(t)\sin\psi(t) + v(t)\cos\psi(t) + U_{cy}. \tag{9}$$

The vessel's momentary position is obtained by intergrating (8) and (9).

Table 1. List of parameters for the 'De Keizer' model scaled for the '*Esso Osaka*', draught 280000 dwt, nominal speed 7 knots

$L = 343$ *metres*
$K^* = 3{\cdot}3$
$K_u^* = 1{\cdot}0\ 10^{-3}$
$\tau^* = 2{\cdot}6$
$\tau_v^* = 12{\cdot}0$
$\alpha_1 = 1{\cdot}4\ 10^{-3}$
$\alpha_2 = 9{\cdot}15$
$\gamma^* = 6{\cdot}0\ 10^{-3}$

The model was scaled according to full scale trial results with the '*Esso Osaka*' (Abkowitz, 1980) using PSI simulation software (Van den Bosch, 1981). A list of model parameters is presented in Table 1.

## KEY WORDS

1. Sea. 2. Human factors. 3. Displays. 4. Automation.