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Error Detection in the Navigational Watch Based on the Behavior Analysis of Navigators

C. Nishizaki
National Maritime Research Institute, Tokyo, Japan

T. Takemoto
Tokyo University of Marine Science and Technology, Tokyo, Japan

ABSTRACT: Poor lookouts, i.e. one of errors in situation awareness, are pointed out as the major cause of collisions of ships, through investigations of collision accidents. In order to evaluate safety measures for preventing collisions caused by poor lookouts, it is necessary to understand background factors, so called "contexts", of errors in situation awareness regardless of occurrence of collisions. The purpose of this study is to point out the possible significant contexts, using a navigator's situation awareness model. As a result, we point out that one of the possible significant contexts is a problem on judgment of priority levels of other ships with regard to attention.

1 INTRODUCTION

Poor lookouts, i.e. one of errors in situation awareness, are pointed out as the major cause of collisions of ships, through investigations of collision accidents. Investigations have long been carried out on navigators' errors that contributed to ship collisions (Romer 2009, Takemoto 2007, Corovic 2013). Especially there are many investigation based on accidents' reports.

In the second generation human reliability analysis such as "Cognitive reliability and error analysis method (CREAM)", accidents caused by human errors are defined as final results and there are many background factors, so called "contexts", in human errors (Hollnagel 1998). In order to evaluate safety measures for preventing collisions caused by poor lookouts, it is necessary to understand the contexts of navigators' errors in situation awareness. However, the contexts of errors in situation awareness during ships' navigation have not been fully investigated. In order to understand the contexts in detail, it is not sufficient to investigate only accident reports and errors not resulted in collision accidents should be also investigated. For the investigation of such contexts, bridge simulator experiments are effective, for the reason that human activities can be observed in detail.

The purpose of this study is to point out the possible significant contexts of errors in situation awareness. For this purpose, we analyzed the human activities obtained by bridge simulator experiments based on "error mode", i.e. classes of human activities. Eight basic error modes have been already defined by Hollnagel (Hollnagel 1998). In this study, navigators' errors in situation awareness are identified through the analysis. The contexts of errors in situation awareness are estimated based on the results of detailed observation of human activities in particular of the identified error cases.

In the previous study, one of the authors proposed a method for identifying navigators' errors in watch keeping based on the behavior analysis of results of bridge simulator experiments, and a situation awareness model was developed to describe the contexts of those errors (Nishizaki 2010, Yoshimura 2012). For the identification, navigators' errors should be determined, and for the determination of such errors, it is essential to select ships having risks of collision correctly. In the previous study (Nishizaki 2010), the risks of collision had been determined based only on "Distance of Closest Point of Approach (DCPA)". However, it had become evident that the selection of ships having risks of collision was not sound in the previous study. Then we analyzed errors in situation awareness again, using the data obtained in the previous study, with a new method for evaluating risks of collision.

In this study, taking into account the deficiency of the pervious study, ships having high risks of collision are redefined based on a "subjective risk assessment index" (Hara 1990, Nakamura 1996) and navigators' errors in watch keeping are identified.

2 PROCEDURE FOR ANALYSIS

The procedure for analysis used in this study consists of six steps as shown in Figure 1. In the first step, experiment scenarios are developed for observation of navigators' error in situation awareness. For this purpose, scenarios under heavy workload are used for the experiments.

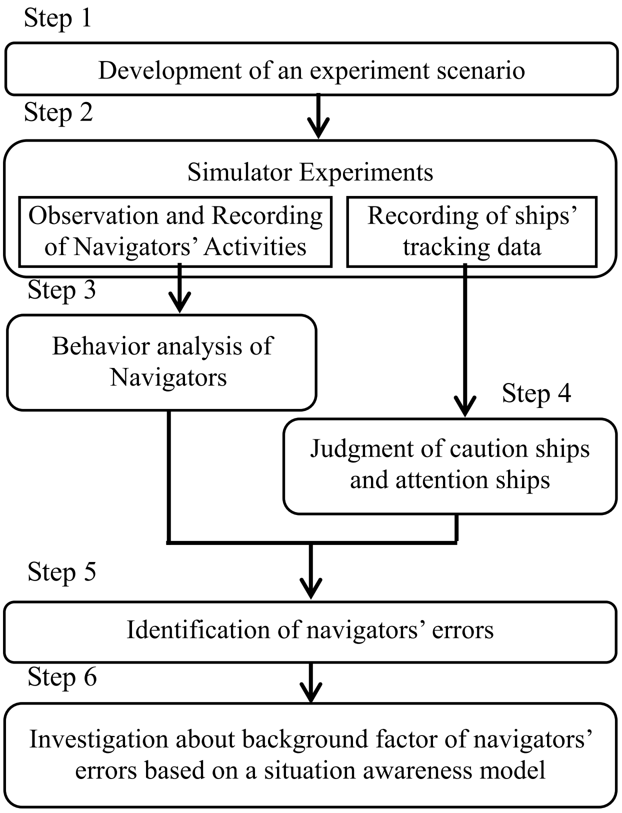

Figure 1. Procedure for analysis.

In the next step, simulator experiments using the scenario are performed to observe navigators' activities. Simulator experiments and observation of navigators' activities are described in detail in chapter 4.

In the third step, information on navigators' situation awareness is collected by the behavior analysis of navigators' activities during simulator experiments.

As the fourth step, the caution ships and the attention ships, which are determined in chapter 3, are judged based on tracking data in simulator experiments. Here, ships having high risks of collision are redefined based on a "subjective risk assessment index" in this study.

In the fifth step, navigators' errors in watch keeping are identified based on the redefined ships having high risks of collision. An evaluation method of navigators' situation awareness is described in detail in chapter 3.

As the final step, the contexts of these errors are investigated using the navigators' situation awareness model. This situation awareness model is described in detail in chapter 5.

3 EVALUATION METHOD OF NAVIGATORS' SITUATION AWARENESS

Indexes of collision risks in ship navigation have been proposed by some researches. In our previous study, we used DCPA as an index of risks of collision to define whether a ship had high risk of collision, for the reason that DCPA was one of simple indexes that could be calculated easily (Nishizaki 2010). However, it is not necessary to require keeping constant watch on a ship of which the estimated DCPA becomes zero at a certain time. Therefore, in this study, we used a subjective risk assessment index (Hara 1990, Nakamura 1996) focusing on rate of relative bearing change of a target ship to define whether the ship had risk of collision. The subjective risk assessment index was designed based on encounter situations of multiple ships, while the other indexes, such as the Collision Judgment threshold value (CJ-value) (Kobayashi 1976), the Subjective Judgment value (SJ-value) (Hara 1995), and the Obstacle Zone by Targets (OZT) (Imazu 2002), were designed based on one-to-one encounter situations.

When a relative bearing of a ship does not change, navigators identify the ship as the target ship having high risk of collision. Therefore, it is rational to use a relative bearing as an index to identify the ships having high risks of collision. Furthermore, it is rational to use relative distance as the other index. In this study, "caution ship" and "attention ship" are identified based on these indexes.

The caution ship is defined as the ship that satisfies all the following conditions (Hara 1990, Nakamura 1996):

$$\dot{\omega} \le \alpha \cdot R^{\beta} \quad (1)$$

where, $\dot{\omega}$ is the rate of relative bearing change, R is relative distance, α and β are weighing coefficients. When the target ship will cross the own ship heading in the future, the relative distance is not more than 1800 m, and when the target ship already crossed the own ship heading, the relative distance is not more than 1500 m.

The attention ship is defined as the ship that satisfies all the following conditions:

$$\alpha \cdot R^{\beta} < \dot{\omega} \leq \gamma \cdot R^{\delta} \tag{2}$$

where, γ and δ are weighing coefficients. When the target ship will cross the own ship heading in the future, the relative distance is not less than 3400 m, and when the target ship already crossed the own ship heading, the relative distance is not more than 3700 m.

The values of α, β, γ and δ are set based on the experimental data of 30,000 points as described below.

$$\alpha = 4.5 \times 10^{5}, \qquad \beta = -1.7$$
$$\gamma = 5.8 \times 10^{5}, \qquad \delta = -1.7 \tag{3}$$

when the target ship will cross the own ship heading in the future,

$$\alpha = 3.0 \times 10^{5}, \qquad \beta = -1.7$$
$$\gamma = 1.9 \times 10^{5}, \qquad \delta = -1.6 \tag{4}$$

when the target ship already crossed the own ship heading.

The caution ship and the attention ship are identified according to the above mentioned criteria by using tracking data in simulator experiments every moment. Navigators' situation awareness are evaluated by whether or not navigators recognized the caution ships and the attention ships at the moment. In the evaluation, error is defined as a navigator's activity that constant watch is not kept on all "caution ships" and "attention ships".

4 SIMULATOR EXPERIMENTS

4.1 *Experimental Scenarios*

The purpose of simulator experiments was to obtain data on navigators' activities in watch keeping in order to collecting information on situation awareness. An open sea was selected as the area for the experimental scenarios to concentrate navigators' activities on watching for ships. In the scenario, there are six ships in relatively-narrow sea area to realize heavy workload of subjects, i.e. navigators, in charge of the experiments.

Ten scenarios were used in the experiments. Figure 2 shows experimental scenario situations. Three ships are approaching from the port side of the own ship, and another three ships are approaching from the starboard side of the own ship. The initial positions of the all six ships are distributed from 4 to 6 nautical miles (NM) from the own ship. Speed of each ship is fixed until experimental scenarios are finished. Each ship is approaching in collision courses (DCPA = 0) at 3 NM from the own ship and the ship keeps the collision course for 240 second. The crossing angles of other ships at 3 NM from the own ship were 40 degrees (P1), 60 degrees (P2), and 80 degrees (P3) in the port side, 30 degrees (S1), 50 degrees (S2), and 70 degrees (S3) in the starboard side. Each scenario has different ship movements such as courses to approaching 3 NM line form the own ship, speeds, crossing angles after collision courses.

The environmental conditions were defined as follows: the weather was fine; visibility was 4 NM; and wind, wave and current were none. Subjects detected each ship by the radar at the beginning of each experiment, and each ship became visible gradually.

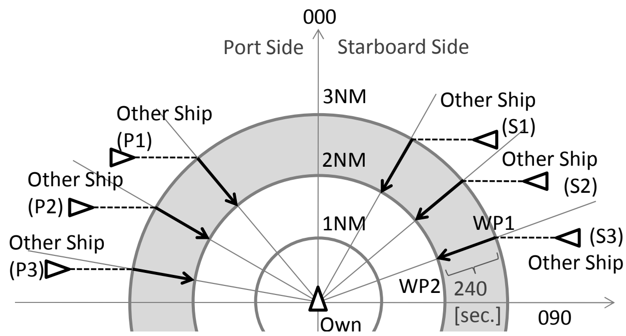

Figure 2. Experimental scenario situations.

4.2 *Experimental Conditions*

Simulator experiments were performed in the bridge simulator of National Maritime Research Institute (Yoshimura 2007). This bridge simulator has a behavior analyzing system with observation and recording system of subjects' activities and voices.

Sixteen subjects who had enough experiences on board were chosen for the experiments. During experiments, they performed navigational watch with a helmsman in the bridge. They were keeping watch with the standard navigational equipments, i.e., compass, binoculars, radar, chart, electronic chart display and information system (ECDIS), and air whistle. Communications with VHF radio were not utilized. The subjects were instructed to perform three tasks as described below.

1 Try to navigate as usual and maintain a safe navigation.
2 Declare the relative bearing of the perceived ship measured by compass when respective ships are perceived at first by visual contact.
3 Declare when they notice something on the respective ships' states.

The initial course of the own ship was north and the own ship was put on autopilot. The initial speed of the own ship was 12 knots. All subjects were instructed to maintain autopilot as long as possible. However, when they determined the need for action to avoid collisions, they could change the course by ordering to the helmsman and the speed by operating the engine telegraph by themselves.

We analyzed the navigators' activities while the own ships was keeping the original courses, for the reason that the crossing angles of ships were changed when the own ship course was changed by the subjects. Each experiment ended in about 30 minutes.

5 RESULTS

Figures 3 and 4 show examples of results of analyses of the records of observations by subjects. In each figure, the ordinate indicates identifier of ships generated during the experiments and the abscissa indicates the time from starting of the experimental scenarios. Gray closed circles on the lines for respective ships indicated by the ordinate denote the times when subjects pay attention to the ships. From this closed circle symbols, it is obvious that there are two watch patterns: subject pays attention to plural ships at once; and subject pays attention to one ship. Cross symbols denote the time when the subjects perceive respective ships by visual contact, and black open circles denote the time when the subjects notice a change of respective ships' states.

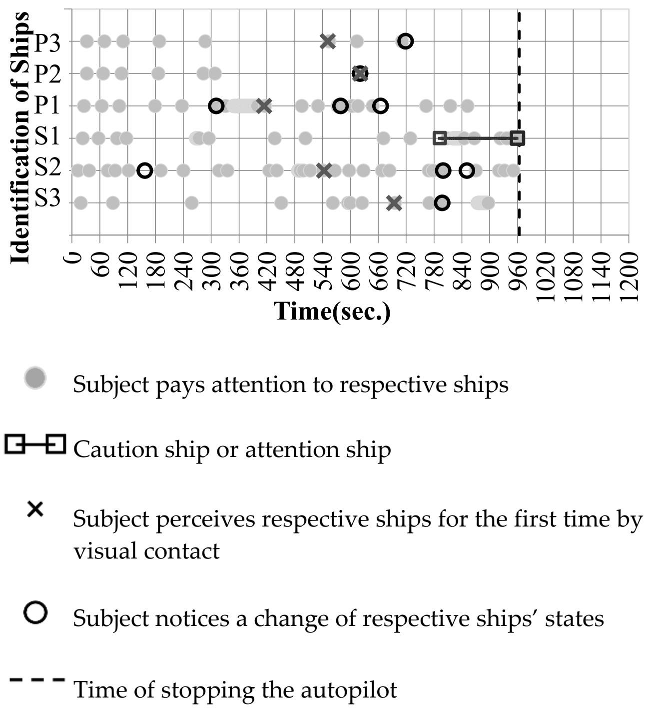

Figure 3. Example of results of analyses of records of observations by subjects in no error case.

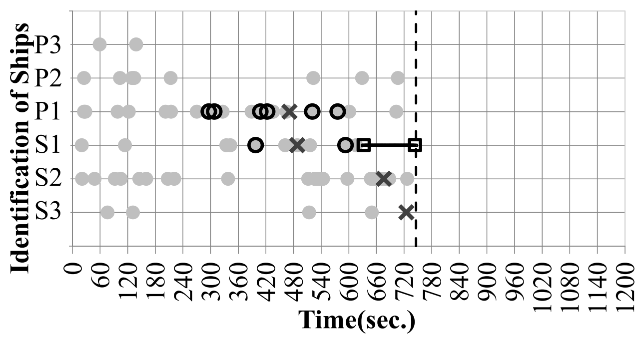

Figure 4. Example of results of analyses of records of observations by subjects in error case.

The caution ship and attention ship are indicated by open squares with sold line. In the experiment reported in Figure 3, other ship S1 is the ship having high risk of collision during 750 to 950 seconds and should be watched constantly during this time. Dashed line in the figure shows the time of stopping autopilot operation.

Ships S1 and P1 have become caution ships or attention ships in many cases. Ships S1 and P1 navigated near the own ship or in front of the own ship. This means that the definitions of ships having high risks of collision are consistent with the ordinary sense of navigators, taking into account that navigators tend to focus on ships near the own ship course line in general. In simulator experiments, most of subjects manually maneuvered to avoid ship S1 or P1. There was no collision in all the experiments.

A classification of human activities that may lead to serious accidents is called "error modes", and eight basic error modes were already defined by Hollnagel as shown in Table 1 (Hollnagel 1998).

Table 1. Basic error modes (Hollnagel 1998).

No.	General effect	Specific effect
1	Timing	Too early Too late Omission
2	Duration	Too long Too short
3	Force	Too little Too much
4	Distance/magnitude	Too far Too short
5	Speed	Too fast Too slow
6	Direction	Wrong detection Wrong movement type
7	Object	Wrong object
8	Sequence	Omission Jump forward Jump backwards Reversal Wrong action

Table 2. Results of error detections.

S.ID *	Num. of Exp. **	Num. of SCS ***	Num. of CS & AS ****	Num. of detection errors	
				Delay of attention	Discontinuation of attention
I	13	78	4	0	2
II	12	72	8	0	1
III	11	66	9	1	2
IV	11	66	15	0	3
V	10	60	8	0	1
VI	10	60	15	0	2
VII	7	42	4	0	1
VIII	7	42	6	1	1
IX	5	30	2	0	0
X	3	18	1	0	0
Total	89	534	72	2	13

* Identification of scenario
** Number of experiments
*** Number of ships analyzed in this study
**** Number of ships which were caution ships or attention ships or both

As the results of the analysis on subjects' situation awareness, two types of errors were identified. These types of errors are classified into "timing" in the basic error modes. One of the types of errors was "delay of attention", i.e. navigator's attention to a ship having high risk of collision was late. Another error was "discontinuation of attention", i.e. navigator's attention to a ship having high risk of collision was discontinued after the first perception. Table 2 shows numbers of errors of respective types identified in the experiments for respective scenarios. As shown in the table, discontinuations of attention were identified in the experiments on eight scenarios. On the other hand, delays of attention were identified in the experiments on two scenarios. We analyzed navigators' situation awareness for 534 ships in total, and 72 ships became "caution ship" or "attention ship" or both. The total number of errors identified was 15. In this study, the frequency of errors is defined as the number of errors identified par total number of caution ships and attention ships. Therefore, the frequency of errors is about 21 %, i.e. 15/72, in all experiments, where subjects are kept under heavy workload situation.

6 DISCUSSION

6.1 *Navigator's situation awareness model in watch keeping*

It is well known that other ships are prioritized by navigators with regard to attention. The priority level of a ship can be estimated based on number of attentions to the ship per unit time. For example based on Figures 3 and 4, the number of attentions per unit time is the total number of gray closed circles, cross symbols and black open circles corresponding to each ship within the unit time.

In the previous study, we judged priority levels of other ships determined by each subject, based on results of analyses of the records of observations by subjects. A surveillance list is a fictitious list for expressing the priority levels and update of the surveillance list corresponds to change of priority level.

A situation awareness model was developed to describe contexts of errors in situation awareness (Nishizaki 2010, Yoshimura 2012). Figure 5 shows the navigators' situation awareness model. This model was developed based on Endsley's situation awareness model (Endsley 1995). The navigators' situation awareness model enables to describe the situation awareness when a navigator pays attention to plural ships simultaneously. In this model, it is assumed that the surveillance list is continuously updated depending on change of the navigators' situation awareness, which always results in change of priority levels with regard to attention. For example, when a new ship is perceived, the ship is added in the surveillance list.

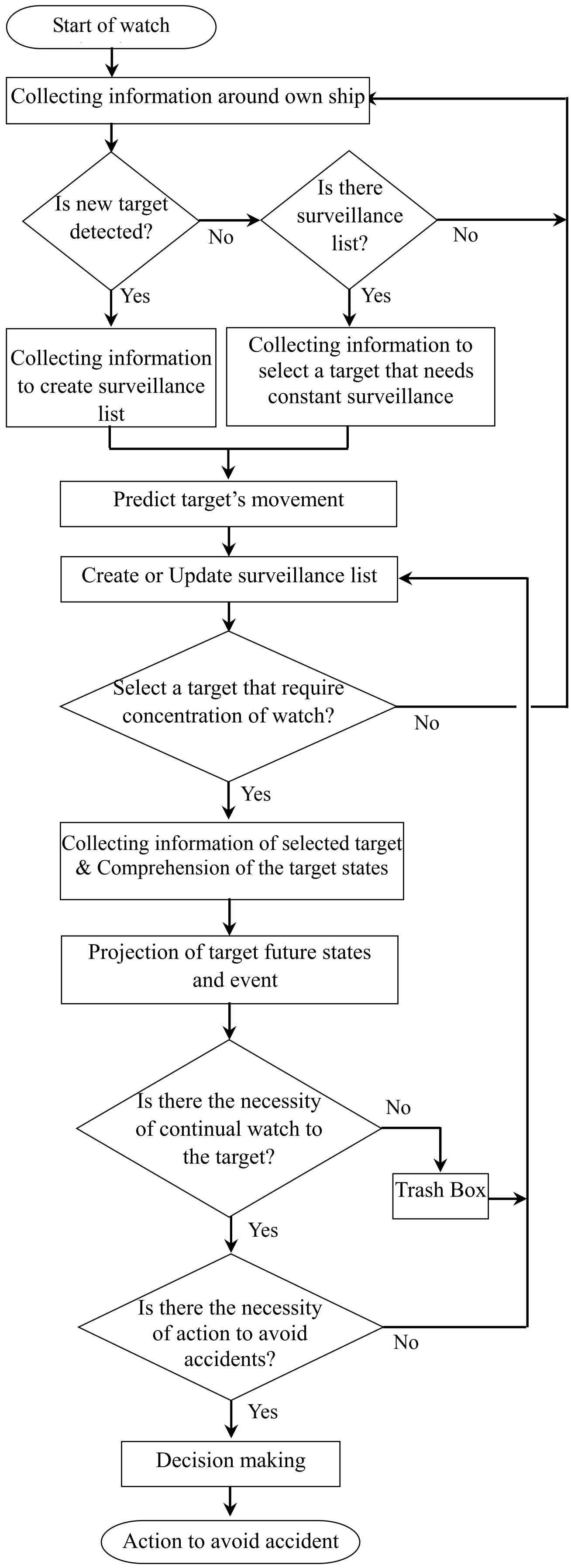

Figure 5. Navigators' situation awareness model.

In this study, priority levels of target ships with regard to attention were estimated for many cases including 72 cases with caution ships or attention ships.

6.2 *Context of errors in situation awareness*

The contexts of errors in situation awareness were investigated, using the navigators' situation awareness model, based on the 15 errors identified through the analysis. As the results of the investigation, it was found that, in error cases, navigators have not paid attention to target ships when the ships were having high risks of collision, though the ships were perceived before. For example in the case expressed in Figure 4, though the attention should be paid to ship S1 during 630 to 780 seconds, the navigator had paid attention to ships other than ship S1 during that period. Thus, it can be concluded that one of the possible significant contexts of errors in situation awareness is a problem on judgment of priority levels of ships with regard to attention. In other words, incompleteness of updating of the surveillance lists is one of the possible significant contexts of errors in situation awareness.

Here, we discuss the causes of the problem on judgment of priority levels under heavy workload situation. Taking into account the navigators' situation awareness model shown in Figure 5, the following three issues can be enumerated as the possible causes of the problem:

- lack of acquisition of information;
- misjudge on prospect; and
- misjudge on continuation of attention.

It is further observed that only a part of the surveillance list has been updated repeatedly in a certain number of cases. This type of updating is one of the types of incomplete updating of the surveillance lists.

6.3 *Conditions of occurrence of errors*

We investigated the features of ships to which attention was paid at a certain time, other than ships having high risks of collision at that time. Then, we found the following two features of such ships:

- ships with lower risks were closer to the own ship than the ships having high risks of collision around 0.5 to 1.5 NM; and
- approaching angles of ships with lower risks were 35 to 45 degrees as far as based on the experiments without over-taking ships, and encounter situations of the ships continued for long time, here approaching angle zero means that courses of both ships are the same.

Namely, existence of a ship, with lower risk of collision, having one of the above mentioned two features is a possible condition for occurrence of errors in situation awareness.

7 CONCLUSION

The contexts of errors in situation awareness under heavy workload were investigated based on the results of analyses of the records of observations, using navigators' situation awareness model. The conclusions in this study are shown below.

1. We identified two types of errors in situation awareness, i.e. "delay of attention" and "discontinuation of attention".
2. One of the possible significant contexts is a problem on judgment of priority levels of other ships.

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