The operational potential of an In-Flight Weather Awareness System: an explorative pilot-in-the-loop simulation

Simone Rozzi1, Stefano Bonelli1, Ana Ferreira1, Linda Napoletano1, & Loïc Bécouarn2

1Deep Blue s.r.l., Rome, Italy
2Thales Avionics, Bordeaux, France

This study investigates the operational potential of an in-flight weather awareness system displaying weather hazard cues that are either invisible (i.e. Clear Air Turbulence and Icing) or visible only during clear visibility operation (i.e. Cumulonimbus, and Volcanic Ash). The study focuses on investigating (i) the potential uses of the display, (ii) its usability deficiencies, and (iii) its potential for pilot error. Methodology: A small-scale human-in-the-loop simulation coupled with expert observations, followed by a questionnaire and in-depth interviews. A total of 14 professional pilots flew several scenarios using the evaluated display to plan route changes free of weather conflict. Results: The display exhibits the potential to shift weather management from a tactical (5–10 minutes) to a strategic level (up to 1h earlier than today). Cluttering due to multiple overlapping weather areas was the main usability deficiency. Mode error could occur due to poor indication of weather hazard status, and when using the proposed display in less modern airspaces than Europe and US. Value: These findings are relevant for human factors and safety specialists and researchers involved in the development, evaluation, purchase and certification of aviation weather displays.

Introduction

For operators of complex systems it is important to respond effectively to the hazardous events that can affect the safety and efficiency of the processes they control. In aviation, the availability of digital displays offers a unique opportunity for safer and more efficient pilot’s response to weather hazards. At the same time the development and introduction of any of such displays calls for a thorough evaluation of their actual impact in the context of use, i.e. the flight deck.

This paper presents a small-scale pilot-in-the-loop simulation aimed at evaluating the operational potential of an in-flight weather awareness system. This system provides pilots with a large-screen and intuitive view of the flight 4D trajectory—the three spatial dimensions of aircraft trajectory plus time—complete with the surrounding weather hazards.

**Background**

*Weather and aviation*

Weather is a long-standing source of disruption in aviation. Besides causing delays, excessive fuel costs and lost passenger time, weather continues to be an important safety concern. NTSB statistics see it as a primary contributory condition in the 23% of aviation accidents (Kulesa, 2003). Adding to this, weather-related accidents are far more likely to cause fatalities than accidents that occur in visual meteorological conditions (NTSB, 2005).

Important hazardous weather events include encounters with (i) cumulunimbi clouds, (ii) clear air turbulence, (iii) icing and (iv) volcanic ash. Cumulunimbi clouds (CB) can cause excessive turbulences, can interfere with communication and navigation systems, and can even lead to engine failure. The consequences of an encounter with clear air turbulences (CAT) can vary from slight discomfort for passengers to potential for structural damage, impaired crew performance and injuries for passengers and cabin crew members (Airbus, n.d.; SKYbrary, 2014). In-flight icing (ICE) occurs when ice accumulates on exposed and unprotected surfaces of the aircraft: this effect can disrupt the smooth flow of air over the wing, thus degrading lift; can generate false instrument readings; and can also compromise the handling qualities of the aircraft. Encounters with volcanic ashes (VA) can result in engine damage and malfunction, since particles can melt within the engine or even disturb the airflow.

When encountering these weather events along the course of the flight, pilots have to devise diversions from the planned flight plan to circumnavigate these events while ensuring adequate separations from them. One crucial aid to support this reasoning is the on-board weather radar. However, one important limiting factor with this system is the shadowing effect: radar waves are reflected by droplets, so when facing a CB it is not possible to see what is behind it—radar waves are blocked by it. As a result pilots might change the flight path in a way that can turn out to be inadequate the moment they realize what is behind the CB line (Craig, 2012). Also non-technological weather information sources include information provided by Air Traffic Control (ATC), which can inform pilot of Pilots In-Flight Reports (PIREPs) broadcasted by aircraft that have passed previously in the same area of interest. Unfortunately, this information is based on subjective judgment. Also, the pilot gain information about the weather picture during the initial mission planning phase of the flight. However, weather may evolve since the start of the flight.

**ALICIA WAS**

To address the above limitations on in-flight weather management, the ALICIA project (*All Conditions Operations and Innovative Cockpit Infrastructure*), an EU cofounded project in the FP7, has proposed a novel Weather Awareness System (WAS) that displays information about the atmospheric hazards along the 4D trajectory of the flight. The display is touch enabled and is composed of two views (see also Fig. 1):
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- **The top view:** this is the larger view and provides pilots with a 2D birdeye picture of the current flight path and the surrounding weather situation (see also Fig. 2). It uses a different symbology and colour coding for each weather events: CB are displayed as yellow areas; CAT as magenta small arrows; ICE as blue areas; and VA as dark-to-grey areas depending on ash concentration—with dark representing the higher VA concentration and most dangerous zones.

- **The lateral view:** located below the top 2D view, this view portrays the vertical profile of the flightpath together with the weather events that will cross this path. Colour coding and symbology are the same as for the top view, except that this view shows also the vertical extension of the weather events.

![Figure 1. Top and lateral views of the evaluated display.](image)

On both displays, weather events visualization is not fixed. To avoid cluttering, pilots can choose which weather hazard to visualize by pressing the corresponding touch screen button available on a dedicated menu. When activated, this menu appears over the lateral view. The system is based on ground meteorological data uplinked to the aircraft and it displays the current weather situation (nowcast). The future weather situation (forecast) can be displayed acting on a time-line provided on the right part of the display (not working during the study). The system automatically calculates future conflicts along the flightplan and displays them as red triangles placed on the expected conflict point. It checks the forecasted weather situation along the route according to the future aircraft position (based on the flight management system). Touching the conflict point a menu can be opened and a new route can be calculated by the system and showed as a tick white line. This new route is conflict free and it returns to the original flight plan as soon as possible.
Pilots can accept the new route (and send it to ATC via datalink to be cleared) or refuse it.

![Figure 2. A close up view of the ALICIA WAS top view.](image)

**Theoretical perspective**

The actual benefit that the proposed ALICIA display can deliver requires a qualitative understanding of how this system interacts with the intended operational context. Notably, a new interface technology is introduced under the lure of quantitative and measurable performance improvements in areas such as capacity, cost-effectiveness, and safety. However, the ability of the technology to deliver on these areas requires consideration of how the new system can be actually used by the human practitioner in context. Two arguments can be made in support of this point. First, stakeholders located at higher hierarchical level than operations, such as senior management, modernization and programme leaders, may tend to assume a direct linear relationship between the new technology and the desired improvements, i.e. the provision of the new technology will attain the desired system (wide) objective(s).

However, such an assumed relationship may actually prove simplistic when compared against the reality of the operational context in which new technology will be used. Technology is imperfect, and operational experience indicates it can be clumsy and difficult to use. It is often the case that the practicalities of fitting the new technology to the work needs to be worked out by practitioners themselves in order to adapt it to the work environment and get the job done (Cook, Nemeth, & Dekker, 2008; Cordesman & Wagner, 1999; Demchak, 1991). One of the possible outcomes of this tailoring process is the use of the new technology for purpose(s) other than the intended prescribed one(s) (e.g. using the on-board anti collision alert system as separation aid). Furthermore, technology can change the nature of the work in undesirable ways: it can redistribute workload unevenly across different phases of the flight, it can deskill human operators, it can make the functioning of the system more obscure to its user, it can increase the potential for surprise (e.g. Chialastri, 2012; Degani, 2004; Sarter, Woods, & Billings, 1997; Bainbridge, 1983).
In safety critical domains, changes such as these may introduce new paths to disastrous failure that did not exist prior to the introduction of the new technology (Strauch, 2004; Woods, Dekker, Cook, Johannesen, & Sarter, 2010).

These considerations lead to the second argument: the actual use of new technology is not something that can be easily assumed or anticipated without appreciating the situational or contextual perspective of the end user. New automated systems are not introduced in a vacuum in fact, but into an existing on-going field of practice made up of people and technological artefacts (Woods et al., 2010). Here, the human strives to meet the multiple and often conflicting demands of the job under intense organizational pressures for productivity, high environmental uncertainty, and limited attentional and temporal resources (Hollnagel, 2012; Hollnagel & Woods, 2005). Thus, the potential of new technology requires consideration of the expert and contextual view of human operators: because they have a first-hand direct understanding of their field of practice, of its intrinsic complexities, trade offs, demands, and uncertainties (Dekker, 2004), operators are best placed to know how they will use the new artefact, for which purposes and which problems may arise in the process. These aspects are not easily intelligible for stakeholders located at higher organizational levels, such as management and engineering, as they lack temporal and spatial proximity to the complex dynamics of the operational environment.

Objectives

The above considerations emphasize the importance of conducting qualitative explorations about the potential of new technology in a way that accounts for the viewpoint of the expert practitioners (the target user) since the very early developmental stage. This is particularly important in the case of technology-centered development processes (Boy, 2012), which may lack a thorough exploration of the role of the novel technology prior deployment. The present study aims at exploring the interaction between the proposed display and the target operational context. In particular it focuses on investigating:

(i) The potential uses of the display, i.e. what pilots believe they could do with the system;
(ii) Its usability deficiencies, i.e. which aspects of the display may hamper access and manipulation of information;
(iii) Its potential for human error, i.e. what error can occur during the use of the display.

Methodology

Location and Equipment

This study was conducted at Thales Avionics over the period Sept 13–Jan 14 in Bordeaux. It made use of a two-person crew fixed based cockpit simulator called Avionics 2020. The evaluated display was located on a central head down
navigation display (size=19inch) that was visible to both the non-flying and the flying pilot, as shown by Fig. 3.

![Navigation display](image)

*Figure 3. The position of the ALICIA WAS in the simulator used for this study.*

**Participants**

14 professional pilots from three European airlines and two European aircraft manufacturers participated voluntarily in the evaluation. Three pilots had previous military experience as jet fighter pilots. Flying experience ranged from a minimum of 2600 flight hours to a maximum of 20000 flight hours, with an average of 8960 flight hours. All pilots were men, their average age was 53 years, with the oldest participant being 68 years old and the youngest 35 years old (sd=10 years). All pilots were familiar with electronic displays. All but two pilots were familiar with touch screen. All but four pilots reported to have flown with head up displays. The participants provided their written consent to participate in the study, and completed a biographical questionnaire.

**Scenarios and Task**

Three En Route scenarios were played: a flight from Amsterdam Schiphol to Clermont Ferrand Auvergne with CB encounters; a flight from Amsterdam Schiphol bound to Brest Britagne airport with CAT and ICE encounters; a flight from Barcelona to Istanbul with VA encounter. Each scenario lasted approximately 30 minutes and was flown by a crew of two. At the start of the scenario the crew was requested to use the ALICIA display to devise collaboratively potential route changes to their planned flight plan. The crews were also invited to explore the various display functionalities, and to report out loud their opinions and criticisms about the value of the displayed information features and the quality of interface management.
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Data collection

During each simulation run, human factors researchers took observational notes of pilots’ behaviours. These captured the unfolding pilot interaction with the display, pilot-to-pilot interactions, as well as pilots’ comments and impressions about the evaluated system.

After completing the three runs, the pilots completed a questionnaire. This collected biographical data and ratings to ten items that evaluated pilots’ perspective on these areas: safety, situation awareness, weather conflict avoidance, punctuality, efficiency, workload, usability, basic task, standardization. Each rating was on a 5-point Likert scale (1=highly disagree; 5=highly agree). The questionnaire was refined before applying it in the study and was administered online: this means that participant ratings were available for subsequent interviews and the final debriefing.

Upon completion of the questionnaire, the rationale behind each rated item was probed by means of in-depth interviews. These developed consistently with the principles of the Critical Decision Method (Hoffman, Crandall, & Shadbolt, 1998; Klein, Calderwood, & Macgregor, 1989): whenever a pilot reported a display problem or benefit, he was prompted to think of a relevant real life scenario to explain what role the display could play, considering the specific scenario demands, constraints, available information cues usually attended, and the likely mistakes that could occur if things go wrong. During this process, pilots were invited to sketch the described situation to clarify the underlying spatial-temporal reasoning. Each interview lasted between 30 to 45 minutes. They were recorded and transcribed.

Data Analysis

Descriptive statistics was used to report the questionnaire results. The Emergent Theme Analysis (Wong & Blandford, 2002) approach was used to analyse interview data. This qualitative method is suitable for making sense of large interview data about expert knowledge in safety critical domains. Initially the data was searched for broader themes, i.e. meaningful portion of the data that in this study captured capabilities and limitations of the evaluated display. Subsequently, the data was searched for sub-themes, i.e. data fragments that support and allow to refine the higher level broader theme they belong to. Sub-themes identification and description made use of a framework composed by four categories: aircraft situation, demand for the pilot, available information cues, and role of the display in the specific situation. After completing the analysis, early results have been presented to the participating pilots for corroboratory purposes during a one-day post-simulation meeting.

Results

Questionnaire ratings in Table 1 indicate that the participating pilots assigned high scores to almost all of the investigated aspects (agreement rates are between 4 and 5 for all statements). In particular, the areas of safety, situation awareness, efficiency and workload are rated quite high, thus indicating that the display was perceived to bring a positive impact to the management of weather. Autonomy was cautiously
agreed as pilots regard weather related decisions as a pilot’s decisions that can be done without ATC support—and the ALICIA WAS does not alter this situation. The area of basic tasks received the highest rating and refers to the fact the display was viewed as not disruptive of existing cockpit activities.

Table 1. Questionnaire category mean, standard deviation, and minimum and maximum. Likert Scale (1=highly disagree; 5=highly agree).

<table>
<thead>
<tr>
<th>Category</th>
<th>Mean</th>
<th>SD</th>
<th>Min</th>
<th>Max</th>
</tr>
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<tbody>
<tr>
<td>SAFETY</td>
<td>4.00</td>
<td>0.80</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>SITUATION</td>
<td>4.67</td>
<td>0.49</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>AWARENESS</td>
<td>1.22</td>
<td>1.22</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>AUTONOMY</td>
<td>4.17</td>
<td>1.03</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>CONFLICT</td>
<td>4.98</td>
<td>0.67</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>AVOIDANCE</td>
<td>4.59</td>
<td>0.52</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>PUNCTUALITY</td>
<td>4.42</td>
<td>0.67</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>EFFICIENCY</td>
<td>4.33</td>
<td>0.76</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>WORKLOAD</td>
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<td>0.29</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>USABILITY</td>
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<td>0.40</td>
<td>4</td>
<td>5</td>
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<td>STANDARDIZ</td>
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Potential uses

The analysis of the interview data was instrumental to interpret the questionnaire ratings. Pilots reported that, compared to today systems, ALICIA WAS can help them to build a comprehensive and intuitive long range picture of the current weather situation, from departure to arrival, that is directly functional to CB, ICE, CAT and VA identification and avoidance. In particular, the following uses have emerged from the study.

C1. Formulating a global diversion, instead of a small range one
Whenever possible, pilots are interested on devising an alternate route clear of conflict from all of the weather hazards that may exist along the originally planned route—rather than implementing minor short range changes to this latter. This latter strategy lacks cost effectiveness because it exposes pilots to the risk of implementing a short range but ineffective change, which requires further close monitoring and adjustment. ALICIA WAS was reported to support the demand for formulating a global diversion because it allows pilots to see the complete weather picture, from departure to arrival. This is information is not available with the current on-board radar.

C2. Anticipating weather management
Pilots commented that the long range weather picture provided by ALICIA WAS facilitates pilot assessment (i) of the existence of dangerous weather conditions at longer distances, and (ii) of the level of threat these pose to current flight route. In turn pilots can make more strategic decisions concerning what should be done—i.e.
formulating a diversion versus continuing the flight without changes—much earlier compared to today’s operations. In their view this was the most significant advantage offered by the display. When asked about how much earlier they could start considering the best (alternative) path considering the current weather situation, pilots reported that that the ALICIA WAS could allow them to think about weather related diversions from 30 minutes to 1h in advance compared to today.

The cost of anticipating weather related decisions is that more effort will be spent by the crew for identifying the best route when still relatively far from adverse weather areas; however, pilots reported that this added effort is desirable because it can drastically reduce the risk of entering an adverse weather area. This latter is an undesirable situation that places a high burden on pilots to restore the safety of flight.

Also, pilots reported that the potential for anticipating weather management can be greatly enhanced by complementing the current version of the display with information about weather (i) historical evolution and (ii) future evolution. Especially for cumulunimbi, to pilots it is important to understand the growing or expansion rate of these events on both the vertical and the horizontal dimensions. This is particularly important when flying over tropical areas, for there weather fronts can grow very quickly in a short amount of time. Depicting past and future information about the evolution of large (and highly dynamic) CB increases pilot ability to formulate a single successful lateral diversion, i.e. it decreases the risk of selecting a diversion that although appropriate at present time, considering current CB dimensions, will need to be modified at a later time as it intersects the expanded volume of the same CB, which has grown wider in the meantime;

C3. Identifying the best airport to descend to in case of emergency.

Three pilots reported that the system could be helpful during emergency situations to evaluate the weather conditions close to the ground. The display would facilitate and support the choice of the best airport where to land in case of an emergency, considering current position, weather situations, underlying terrains and aircraft (decreased) capabilities. Also the system could be useful during engine out situations, especially when flying over high terrains, to check readily whether there are cumulunimbi or other weather hazards at the maximum flight level that can be sustained by the aircraft.

Missing information cues

Pilots noted that the system was not ready for operational use. They suggested a range of missing information items that need to be provided so that they can work with the system. These are listed below:

- **Weather Information age.** To trust and use the system pilots need to know how old the displayed information is, i.e. when it was calculated. They reported to be afraid of making decisions about diversions based on information that is not valid anymore by the time the decision is made;
- **Width of the section of airspace displayed on the vertical display.** A further missing information was the width of the section of airspace represented in the
vertical display (see Fig. 1). As this display is 2D, depth is not represented, thus pilots miss essential information cues both about (i) the horizontal distance between the displayed weather events and the trajectory of the flight, and (ii) the width of these events.

- **Contextual Weather Information.** Pilots noted that it would be useful if ALICIA WAS supported further inspection of the weather conflict points identified and displayed by the system along the 4D trajectory of the aircraft. Currently, the existence of a weather conflict is signalled by the “R” icon (see Fig. 2). Clicking on each displayed conflict point the pilot can see pieces of information such as time and distance to conflict. Additional details could be provided—such as altitude and severity level of the hazardous weather event in question—so to make the display more informative;

**Usability**

Cluttering induced by colour coding deficiencies was the main usability problem. It occurs when multiple weather areas, i.e. CB, ICE, Turbulence, overlap on the same area of the display. Pilots suggested implementing a filtering function that allows selecting weather events only within a given range, e.g. 1000 feet below and above a given flight level. Aggravating the cluttering problem were the borders of the countries depicted on the map. Their thickness made them unnecessary salient for pilots. Besides cluttering, pilots raised a set of colour coding issues: they favoured a representation of CB areas complete with marked CB boundaries, as this is more consistent with their visual experience of CB as seen from the cockpit seat. Also, they required a more salient colour for ICE, as they would not normally associate blue with a threat.

**Potential for Error**

E1:  **Error Mode: Pilot forgetting the weather visualization when set as idle**

Pilots might fail to notice a CB, CAT, ICE, or VA because s/he might forget that the visualization of any of these weather events has been set as idle. Two conditions of current HMI design can lead to such error: first, no information cue about the visualization state (on/off) of weather events is displayed on the horizontal (strategic) top view of the ALICIA WAS. At the same time this is the area where pilot’s attention concentrates the most in order to acquire weather information. Second, the control panel grouping the touch screen buttons enabling to switch on/off weather events visualization is hidden below the vertical display and is not normally visible if not intently selected. Thus, these two conditions might result in pilots losing track of the selected HMI setting, consequently failing to realize that a relevant weather hazard is not visible only because he or she has not activated its visualization. Partially mitigating this aspects is the fact that even if the display of weather objects is not selected, the system will raise an alert if there is an expected conflict with the flight plan;
**E2: Over Trust: relying on the system when flying over underequipped airspaces**

The continual use of a reliable ALICIA WAS might lead pilots to get used to trusting this system also when flying over regions not enabled with the necessary ground based infrastructure. Pilots envisaged this situation could occur for instance when a pilot normally flying in Europe or US flies over some less equipped regions in Africa or the Middle East. As no weather information would be supplied from the ground to the ALICIA WAS, the crew might think that no weather hazard ahead exist when in fact it does—and s/he could actually be flying into it.

**Discussion and conclusion**

This study has explored the operational potential of an in-flight weather system by means of a small scale pilot-in-the-loop simulation. The study has provided “a preview” into how pilots’ activities may change following the introduction of the evaluated display. In particular, the system was reported to provide pilots with an intuitive long range global view of the weather situation encountered by the aircraft. This can allow pilots to formulate a global diversion when facing hazardous weather events, instead of a short range one. In particular in tropical areas, the display can protect the aircraft from the risk of missing a farther and larger weather front that is rapidly growing behind the closer and smaller CB in front of the aircraft. This can reduce the risk for the aircraft to fly unintentionally into a larger (hidden) storm after having avoided a first CB. Also, the display was reported to have the potential to anticipate weather managements to 30 minutes–1h compared to today, thus shifting weather management from a tactical to a strategic level. Finally, during emergencies, the display can be helpful to select the airport whose weather conditions are more favourable for an emergency landing. These capabilities are directly relevant to the management of weather hazards as today they are not supported by the existing on-board radar.

On the negative side, the display was not considered mature for operational use, for it lacks fundamental information such as weather information age, width of the section of airspace represented in the vertical displays, and contextual weather information. Cluttering due to poor colour coding was the main reported usability problem. Errors in the use of the display could occur if the pilots forgets to turn on weather event visualization, and in case the aircraft flies into sub-equipped airspaces, as these may lack the ground weather data required by the ALICIA WAS.

Overall, these findings provide information useful for evolving the evaluated display concept further—i.e. up to a maturity level appropriate for operational testing and subsequent certification approval. One important aspect to consider is the reliability of the ground based data: although this aspect was assumed to be satisfactory for the purpose of the present study, it will need to be addressed by future developments and evaluations. Beyond the context of this study, the identified findings can provide an initial benchmark available to practitioners involved in the development, deployment and monitoring of weather displays.

From a methodological perspective, the study has the merit of having illustrated one viable approach to explore the operational role of a low maturity display concept.
Literature on safety critical automation suggests that it is important to understand (i) how a novel technology can be used in the field of practice and for which purposes, and (ii) what qualitative changes it can bring. However, the introduction of novel safety critical technologies may neglect the consideration of these aspects; as a result the new technology may be used in ways that deviate from the envisaged and prescribed use, and may introduce new paths to failure. These problems occurs because the development of novel safety critical displays is usually technology centred (Boy, 2012; Jackson, Dorbes, & Pinchacourt, 2000): it is driven by the availability of new technological capabilities, so that engineering development precedes the detailed search of actual potential uses. For instance, in the present case, display development was mostly propelled by the availability of novel enabling communication and data base technologies. In contexts such as these, the use of qualitative human-in-the-loop simulation emphasizing the in-depth understanding of the perspective of expert practitioners seems a plausible approach to shed light into how the new system can fit into the field of practice—in term of its potential uses, usability problems and errors. Such understanding, which has to be refined throughout system lifecycle as new issues emerge, can arguably help leaders and professionals involved in the development, deployment and management of the novel technology to develop more realist expectations about what potential the new system can deliver.

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References

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