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Attentional costs and failures in air traffic control notifications

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Large display screens are common in supervisory tasks, meaning that alerts are often perceived in peripheral vision. Five air traffic control notification designs were evaluated in their ability to capture attention during an ongoing supervisory task, as well as their impact on the primary task. A range of performance measures, eye-tracking and subjective reports showed that colour, even animated, was less effective than movement, and notifications sometimes went unnoticed. Designs that drew attention to the notified aircraft by a pulsating box, concentric circles or the opacity of the background resulted in faster perception and no missed notifications. However, the latter two designs were intrusive and impaired primary task performance, while the simpler animated box captured attention without an overhead cognitive cost. These results highlight the need for a holistic approach to evaluation, achieving a balance between the benefits for one aspect of performance against the potential costs for another.

Practitioner summary: We performed a holistic examination of air traffic control notification designs regarding their ability to capture attention during an ongoing supervisory task. The combination of performance, eye-tracking and subjective measurements demonstrated that the best design achieved a balance between attentional power and the overhead cognitive cost to primary task performance.

Keywords: air traffic control; visual notifications; attentional capture; detection; eye movement

1. Introduction

Notification of important information in multitasking environments is usually achieved through visual cues, sounds or haptics that advise the user of a change in state of the human–machine interface. In critical domains such as air traffic control (ATC), nuclear power or health care, it is important that notifications are made at appropriate times and in an appropriate manner in order to avoid human error with serious consequences (Miyamae 2008). The current study takes a cognitive systems engineering (CSE) perspective whereby the information system and its human operator are viewed as a single unit (a joint cognitive system); the introduction of new technology should therefore team together with the operator to optimise overall performance, such that any benefits in one domain do not incur costs in another. In order to gain a comprehensive understanding of the effects of different notification designs on the cognitive functioning of this integrated human–machine system, it is necessary to use a holistic approach that provides a comprehensive assessment of the impact of the system on cognitive functioning and performance, rather than restricting the evaluation to the function that the system was specifically designed to support (e.g. Lafond et al. 2010). For example, a salient design might be excellent at capturing the operator's attention; however, one that is too prominent may immediately divert attentional resources away from the ongoing activity, incurring other issues such as anxiety and primary task error (e.g. Bailey, Konstan, and Carlis 2001). It is important in dual-task situations that one subtask does not suffer at the expense of another and that an optimal balance is achieved (Navon and Gopher 1979; Wickens 1980). Using a holistic approach that takes into account a variety of assessment dimensions (e.g. notification response time, primary task performance, eye-tracking measures, subjective reports), we evaluate five alternative visual notifications in their capacity to meet the challenges outlined above in the context of supervision and monitoring in ATC.

1.1 *Notifications in ATC*

Radars provide information regarding the state of the airspace, enabling air traffic controllers to make choices and issue commands to pilots. Monitoring and storage of this information is an important part of the task (Duchowski 2007), and the radar screen is a critical interface to display information to the controller unambiguously and without cognitive overload.

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One way to provide information on large or multiple screens, while minimising disruption to the primary task, is to exploit peripheral vision. The human visual perceptual system comprises several parts relating to the angular difference with the point of fixation: foveal area (0–2°), para-foveal area (2°–5°) and the area of peripheral vision (>5°). In operational control centres, the standard set-up uses 66-cm radar screens with controllers positioned at a distance of about 70 cm. The visual comfort zone of 15° (French standard AFNOR NF X 35-101-2) corresponds to a circle of radius 18.7 cm, meaning that information visibility is degraded for substantial portions of the screen. As perceptual performance is impaired away from the centre of vision, parameters such as colour, motion, luminance, opacity, size, time profile and frequency of the signal events should be taken into account in terms of notification design (Athènes, Chatty, and Bustico 2000).

In ATC, on-screen notifications generally rely on colour to alert the controller to abnormal or risk conditions. In peripheral vision, the choice of colour in particular is crucial because perception is not uniform; for example, green is very badly perceived at 30° from the centre of vision, but yellow is discriminated well in the periphery (Ancman 1991). ATC notifications fall into two levels of increasing operational criticality: ‘Warnings’ and ‘Alerts’. Warnings that have lower levels of operational significance are displayed on the radar labels with static red text, while more critical alerts use blinking red/white text. For example, a real-time algorithm evaluates the potential for conflict (Short-Term Conflict Alert) – aircraft must be separated by a minimum of 9 km in the horizontal and 300 m in the vertical plane – and when this rule is violated, a notification is sent to the radar image displaying the flashing message ‘ALRT’.

Vision science demonstrates that peripheral cues can capture attention in a stimulus-driven, bottom-up fashion, but the sudden appearance of a new object will not necessarily reach awareness if attention is focused on a different task or location (Jonides 1981; Theeuwes 1991; Yantis and Jonides 1990). Furthermore, the attentional power of a new stimulus may be reduced in real-world dynamic displays, making it important to consider the display context such as the colour similarity between the target and the background, and the movement of other background elements (Nikolic, Orr, and Sarter 2004). Motion is better detected in the periphery than colour or shape cues (Bartram, Ware, and Calvert 2001), and studies have examined the impact of various motion features such as velocity, amplitude, smoothness and movement type (e.g. linear, zoom, flashing, fading) on the speed and accuracy of notification detection (Bartram, Ware, and Calvert 2003; McCrickard et al. 2003; McCrickard, Catrambone, and Stasko 2001; Ware et al. 1992). Visual alerting has been studied in command and control (C2) environments specifically, such as pilot in-the-loop flight simulations (Iani and Wickens 2007; Nikolic and Sarter 2001; Stelzer and Wickens 2006), ATC environments (Loft, Smith, and Bhaskara 2011) and tactical categorisation tasks (Crebolder 2012). Guidelines have been proposed for designing animated visual signals (Athènes, Chatty, and Bustico 2000), but more research is needed regarding the attentional costs and failures of alerting in data-rich dynamic displays to determine the optimal design that balances noticing against intrusiveness.

An important step forward in the issue of event noticing is a recent attempt to operationally and quantitatively define the nature of salience using a stochastic model, NSEEV (noticing – salience, effort, expectancy, value; Steelman, McCarley, and Wickens 2011). It integrates elements of basic visual perception (e.g. visual search, attentional capture) with an engineering perspective that takes into account supervisory monitoring and the role of the work environment. *Noticing behaviour* is dependent upon the bottom-up *salience* of the item of interest, both static (Itti and Koch 2000) and dynamic salience (Yantis and Jonides 1990), the *effort* to shift attention towards that item in terms of eccentricity from the current point of gaze (peripheral items are reduced in salience), the *expectancy* of the event occurring and the *value* or consequences/criticality of it being missed (top-down attentional settings). The model can be used to estimate both detection rates and response times in dynamic workspaces, and has been validated against empirical data on alert detection (Steelman, McCarley, and Wickens 2011; Wickens et al. 2009a). This modelling effort marks a significant departure from many previous applied studies that have relied upon operators’ subjective reports to gauge notification saliency. In this tradition, the current work will use objective measures to assess the adequacy of visual alert designs.

1.2 Issues for notification design

One concern for a notification system is that seemingly prominent objects in the visual field can sometimes elude attention despite their relevance and importance to the primary task (e.g. Drew, Võ, and Wolfe 2013). This phenomenon of inattentional blindness (Mack and Rock 1998; Most et al. 2005) can occur even when a stimulus is salient in terms of its colour or movement (Mack and Rock 1998), thus posing a challenge for the design of safety-critical emergency alerts. The likelihood of inattentional blindness is increased with the attentional demands of the task (Simons and Chabris 1999), working memory load (Fougnie and Marois 2007), the need to maintain information in visuo-spatial memory (Todd, Fougnie, and Marois 2005), low expectancy of events (Steelman, McCarley, and Wickens 2013) and during periods of high tempo activity with competing visual demands (Nikolic and Sarter 2001; Sarter and Woods 1994). Thus, it may particularly be the case that objects or changes to a visual scene do not reach awareness in complex and demanding C2 environments (e.g. Durlach, Kring, and Bowens 2009); in fact, operators may even look directly at a critical change but not ‘see’ it (e.g.

Vachon et al. 2012). An object is more likely to be detected if it is near the focus of visuo-spatial attention (Most et al. 2000), but proximity is not sufficient for detection and it can still be missed (Newby and Rock 1998; Simons and Chabris 1999). In demanding tasks, operators may experience attentional narrowing or 'tunnelling' (Chan and Courtney 1993; Wickens and Alexander 2009) and become fixated on a particular facet of their task, to the exclusion of other equally – or perhaps more – important aspects of the environment (see Dehais et al. 2010). If operators in these situations do not perceive warnings provided (Beringer and Harris 1999; Dehais et al. 2010, 2012), a technique of cognitive countermeasures might be useful, whereby other on-screen information is removed in order to direct the operator towards the system alert and help disengagement from the current task (see Dehais, Causse, and Tremblay 2011). Such a technique may also be relevant in the case of a 'cry wolf' effect, whereby operators may choose to deliberately ignore warnings, attributing little importance to them in the belief that they are false alarms (Breznitz 1983; but see also Wickens et al. 2009b).

A second problem for a notification system is that the appearance of a new item in the visual field might be too salient and divert attention away from the focal activity to its detriment. Vision science indicates that some features of visual displays can elicit an involuntary, automatic orienting response, for example colour (Bauer, Jolicœur, and Cowan 1996; D'Zmura 1991), luminance (Turatto and Galfano 2000), motion (Faraday and Sutcliffe 1997) or the onset of a new object (Remington, Johnston, and Yantis 1992; Yantis and Jonides 1996; but see also Franconeri, Hollingworth, and Simons 2005), which can slow primary task performance as fewer attentional resources are available for the task at hand. Interruptions are known to have a negative effect on the primary task in terms of human error (Reason 1990), anxiety (Bailey, Konstan, and Carlis 2001), increased task decision-making times (Hodgetts, Vachon, and Tremblay 2014) and reduced situation awareness (St. John, Smallman, and Manes 2005). The impact may be particularly disruptive if there is no time to consolidate important facets of the primary task before switching (e.g. Hodgetts and Jones 2006; Trafton et al. 2003). Thus, although it is desirable that a notification captures attention, it is important that it does not do so at the expense of all other tasks. Designing and evaluating a notification system requires one to establish a balance between the prominence of the design and the ease of assimilation into the user's primary task (Maglio and Campbell 2000; McCrickard and Chewar 2003).

1.3 Eye movements

Many researchers consider that there is no eye movement without a preceding reallocation of attention (e.g. Drieghe, Rayner, and Pollatsek 2005; see also Hoffman 1998). Since fixations and saccades are thought to reflect the user's attention, eye movement analyses can provide a useful way to characterise attentional capture and information processing limitations relating to the task of radar monitoring. Eye-tracking is a non-obtrusive method of gaining indices of cognitive functioning, which is well suited to dynamic situations. It can reflect online information processing (e.g. Pearson and Sahraie 2003; Zelinsky 2008), in terms of where attention is directed on a visual display and how much processing is applied to a particular object. In terms of the current study, eye-tracking can be used among other things as a means of measuring the time needed to detect and fixate these notifications.

1.4 The current experiment

In this paper we address the issue of notification on large screens using an ATC-like synthetic environment. Such microworlds simulate key features of dynamic systems within a controlled setting, while the immersive environment provides a higher degree of external realism than traditional laboratory studies investigating fundamental processes without specific contexts such as piloting and ATC. The LABY microworld (Imbert et al., forthcoming) involves a dynamic visual monitoring radar task (see Figure 1), but the underlying functions make it applicable beyond ATC to a range of surveillance/monitoring tasks. The participant must guide a plane around a given route, avoiding potential conflicts with other (system-controlled) aircraft in the vicinity by inputting numerical values to alter speed, heading or flight levels. Using this experimental platform, we test the attentional power of five notification designs, as well as the ease with which acknowledgement of these alerts can be assimilated within the primary task. Three designs exploit peripheral vision, of which two are current operational ATC designs that correspond to low-level warning (static coloured text) and high-level alert (blinking coloured text), and one is a prototype implemented on a new radar display within the framework of Single European Sky ATM Research (SESAR), a European project which aims at developing the new generation of air traffic management systems. The remaining two are new prototypes of notifications designed to reduce the problem of inattentional blindness by capturing attention in foval vision.

Since controllers' introspective reports may not be a reliable and accurate reflection of their actual performance under different conditions, we will combine the subjective opinions of participants on the different designs with a range of objective performance and eye-tracking measures to gauge the attentional power of the alerts. The NSEEV model points to the importance of dynamic salience in capturing attention, and as such we anticipated that time to perceive and validate the alert would be quicker with the animated alerts than the static text. A further feature of NSEEV is eccentricity from the current point of gaze, whereby peripheral items are less salient. The two designs that use foval vision should result in fewer missed notifications than the three peripheral ones, due to their ability to direct the user's attention from the guided aircraft to the focus of the alert. However, designs that are too prominent may cause unexpected interruptions, forcing the operator to immediately suspend work on the ongoing activity which may subsequently come at a cost to that task. Thus, we look to identify an optimal compromise in the trade-off between alerting task noticeability and ongoing task performance.

2. Method

2.1 Participants

Thirty ATC specialists working for the French civil aviation research centre (mainly engineers and five controllers) volunteered to take part in the experiment. They were all knowledgeable about operational interfaces and about air-traffic controller activity.

2.2 Experimental platform

The LABY microworld is built around a main task of guiding an aircraft around a route shown on the display screen (Figure 1). The device is a simulated environment that uses identical graphical objects and interactions to operational displays. Participants must monitor the correct path of the aircraft and are given instructions to enter control commands using drop menus. These instructions are triggered by the aircraft entering a specific area on the route, and remain active until the correct value is entered or the aircraft leaves that section of the route. They must be followed and any deviation from the given pathway results in an audible signal and a reduction in score. Two types of drop menu were used in the experiment: 83 instructions related to cleared flight level (CFL; Figure 2a), and six were 'Direct' orders (request for direct clearance to a waypoint during a turn phase; Figure 2b). Participants had to click on the relevant item in the aircraft's label (i.e. the current flight level or direct order), which opened the drop menu; values could then be scrolled using the arrow buttons or wheel on the mouse. A baseline LABY study (unpublished) showed that the mean time to enter and validate both

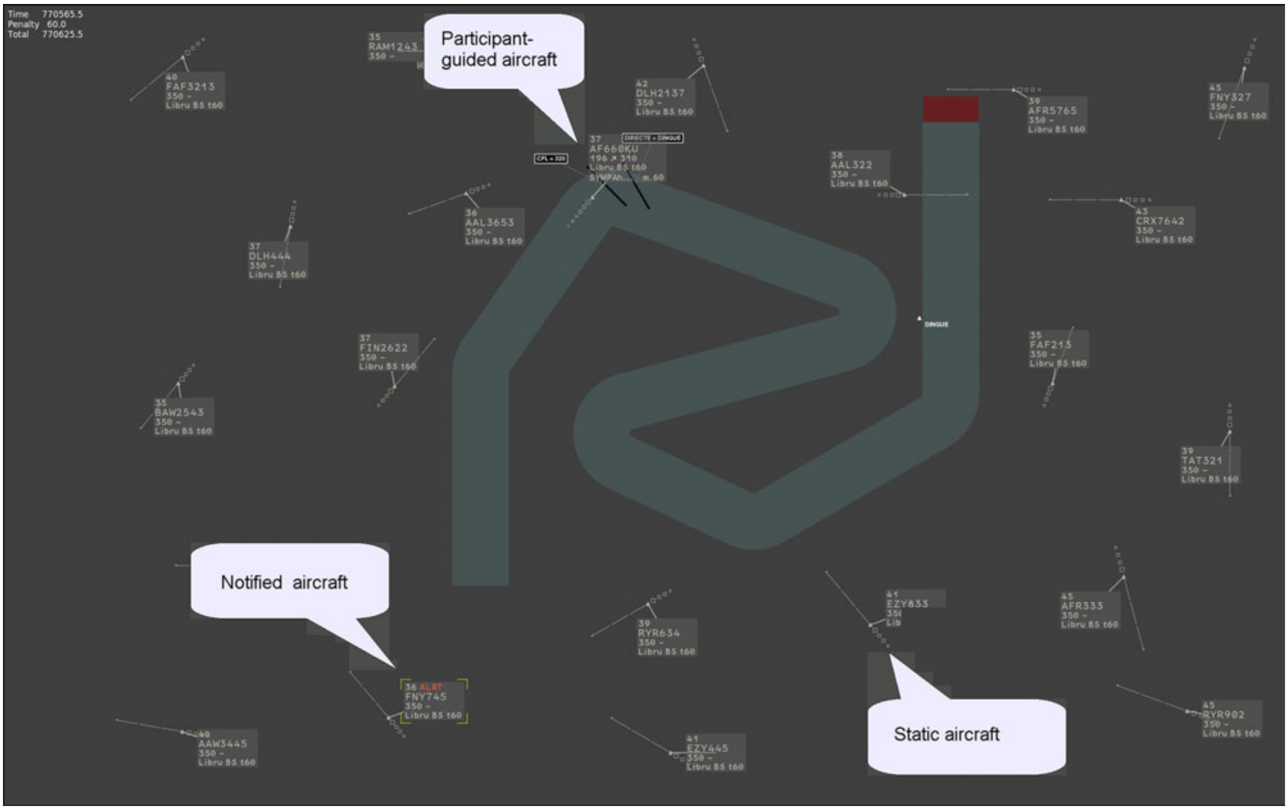

Figure 1. The LABY microworld.

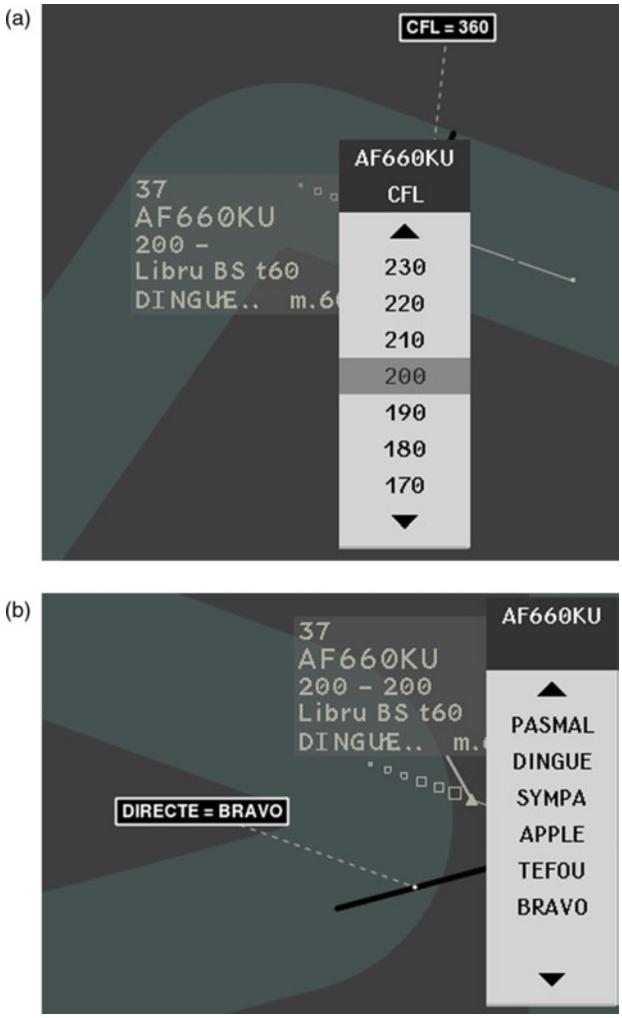

Figure 2. Screenshots of the drop menus for the control task (a) CFL orders and (b) direct orders.

CFL and Direct orders was 3.09 s (variance 0.7 s), while the mean time available for entering orders (mean length of route sections) was 9.14 s (variance 7.07 s).

In addition to this primary task, participants had to acknowledge notifications associated with other static aircraft located in peripheral vision, simulating the display of a radar image. LABY is displayed over a large 66-cm screen. Our intention was to assess the attentional-capturing abilities of randomly selected notifications appearing out of the visual comfort zone of 15° of visual angle, which corresponds to 18.75 cm from the guided plane (15° at a viewing distance of 70 cm). A notification (40 in total; 8 × 5 conditions) was triggered in peripheral vision when the aircraft entered a specific section of the route, in a similar way to the instruction zones described above. Participants were asked to acknowledge it as quickly as possible by clicking with the mouse on the associated aircraft. The notification remained on the screen until it was acknowledged or until the guided plane entered the next section of the route. The mean length of each notification period was 19.62 s (variance 3.1 s). The route sections were designed so that this notification time period always overlapped with multiple primary task events. However, as the notification periods were generally much longer than each response required, more than half of primary task orders were triggered while there was no notification on the screen.

2.3 Types of notification

(1) *Colour* is a static notification that displays the word ‘FNIV’ in an orange–red colour. It corresponds to the design currently used operationally to signify a lower-level warning, and is associated in the experiment with the aircraft’s altitude (see Figure 3a).

(2) *Colour-Blink* is coloured text with the word 'ALRT' which blinks at a rate of 800 ms on/200 ms off (see Figure 3b). It is currently used in ATC for high-priority short-term conflict alerts. Both Colour and Colour-Blink have been operational since 1999.

(3) *Box-Animation* involves the same coloured text 'ALRT' but also four yellow chevrons placed around the label of the notified plane. These chevrons move outwards from the label by 60 pixels following a slow in/slow out animation cycle of 1 Hz. It corresponds to a radar display prototype being used in the framework of the European innovative research programme (SESAR WP 4.7.2.) (see Figure 3c).

(4) *Shadow-Mask* is an animated design that uses the opacity of the background of the radar display to differentiate the notified aircraft (other planes fade out for 300 ms), and at the end of the fade-out animation, the notified object vibrates for 16 × 160 ms to catch the participant's eye (see Figure 3d). The total duration of the animation is 2.56 s, but the radar display remains darker for 20 s or until the participant validates the notification. Such a design is similar to designs inspired by the concept of cognitive countermeasures, whereby other on-screen information is temporarily removed in order to focus attention on the critical aspect and prevent perseveration on less important elements of the task (Dehais, Causse, and Tremblay 2011). In this design, we chose to degrade the visualisation of the non-relevant information instead of removing it completely, and vibration was added to ensure that the participants' attention was captured.

(5) *Halo* is a prototype alert that provides both distance and direction information at a glance. In the opposite way to circles radiating out from a stone dropped in water, the circles start on the edge of the guided plane (current object in focus) and converge inwards onto the notified plane. In this way, the dynamic animation flows directly from the guided plane and towards the alert. The eye is attracted to movement, and attention naturally moves away from the main task and onto the area highlighted by focusing circles (see Figure 4).

2.4 Variables

The independent variable was notification type: during a session, participants received eight notifications of each of the five designs described above (40 in total), using random sampling without replacement. In accordance with our holistic approach, we used a selection of dependent measures that covered the spectrum of processing and cognitive functions involved in this simulated ATC task. These included validation time, eye-tracking measures, the number of missed notifications, primary task performance and subjective reports. Validation time was the time between the onset of the notification and the participant acknowledging its appearance by clicking on the corresponding radar label. As a secondary point of interest, we also looked at validation time as a function of spatial distance between the guided plane and the alert:

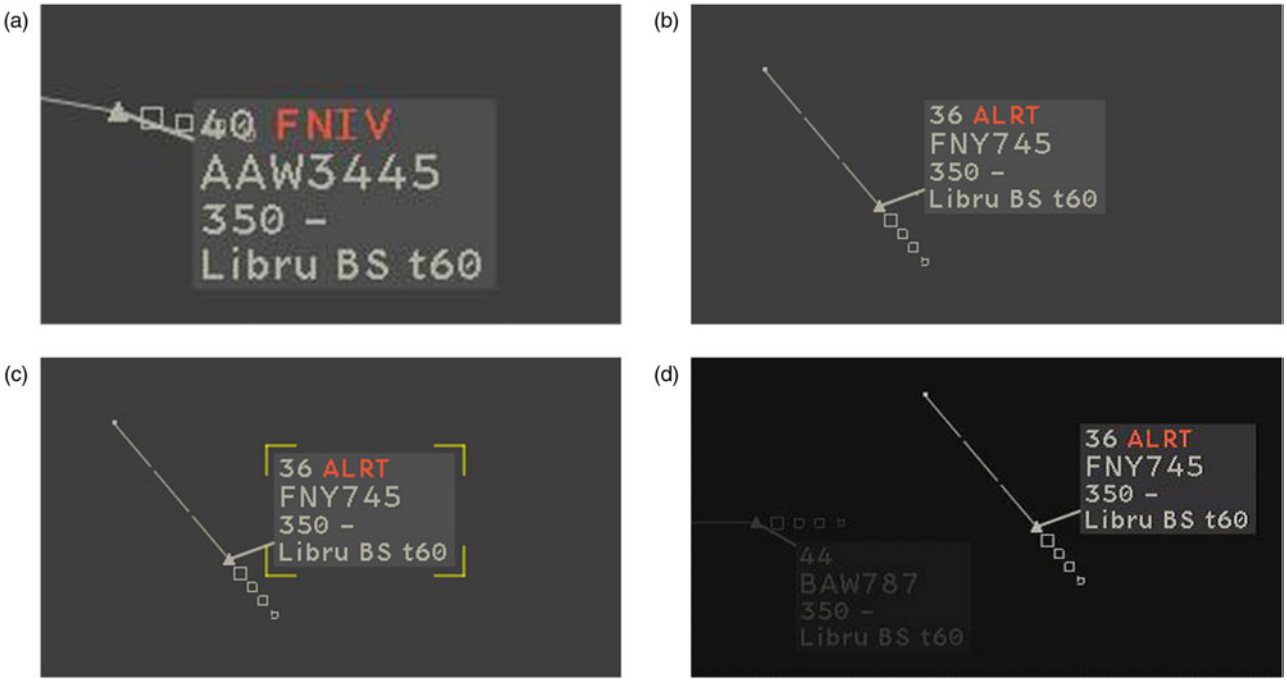

Figure 3. Notifications: (a) Colour, (b) Colour-Blink, (c) Box-Animation and (d) Shadow-Mask.

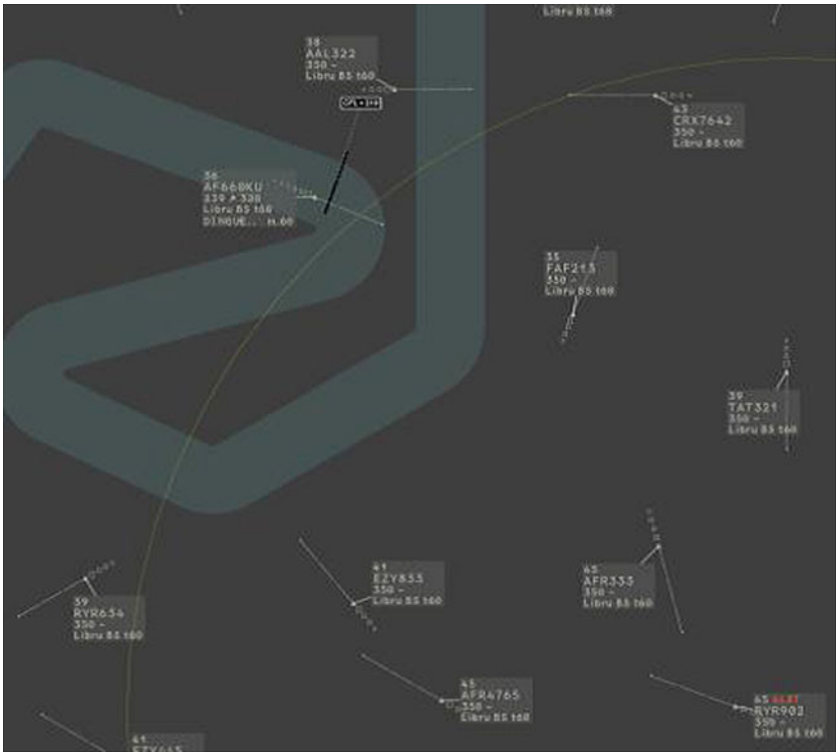

Figure 4. Halo notification.

18.75 to 30 cm, or greater than 30 cm (15°–23° of visual angle, or greater than 23°). French standard norms on acceptable limitations (NF X 35-101-2) define three standard areas: 15° is the comfort zone for colour perception; 15°–30° is considered acceptable (30° is the limit for a correct green and red perception); and over 30° is considered unacceptable. The 23° cut-off was chosen because it is the median value for notification distance. Half of notifications were between 15° and 23°, and the other half were $>23°$. Considering a display at 70 cm from subject's eye, this area represents a circle of radius 18.75 cm on the radar screen. This dichotomous variable was intended to go some way towards determining whether certain notification designs were differentially better/worse at capturing attention when at shorter/further distances from the focus of attention. Eye-tracking data were also collected, which allowed us to further examine the attentional power of the alerts by decomposing the validation time into two parts: the time between notification onset and fixation on the notified plane, and the time between perceiving (fixating) the notified plane and responding to it. We used a FaceLab 5 device without a chin rest, and gaze was tracked remotely using an infrared source and two infrared cameras. The set-up involved a 30-inch display with a resolution of 2560 × 1600, located 70 cm in front of the participant. FaceLab was configured to output 60 -Hz eye-data and head-position data. The calibration phase involved fixating nine points in turn and took about 5 minutes. A fixation was defined as lasting more than 50 ms. To identify which aircraft was fixated, we looked for planes whose boundary box intersected with a square area of side 140 pixels (2.88° of visual angle) centred on the coordinates given by the eye tracker. The static aircraft were separated by 300 pixels. In terms of performance data, we recorded the number of missed notifications (not validated within 20 s) as well as the percentage of errors made on the primary task in each condition.

2.5 Procedure

Participants read standardised instructions presented on the screen and took part in a training phase that typically lasted 10–15 min; they were able to chose when to finish the training exercise once they felt comfortable with using the LABY microworld, so long as they had completed a minimum of two changes of direction. The experimental task lasted approximately 20 min. Afterwards, there was a 30-min debriefing session in which participants had the opportunity to provide their subjective opinions on the five notification designs.

3. Results

One-way repeated-measures ANOVAs were performed to evaluate the effect of the type of notification on each dependent variable. The Greenhouse–Geisser procedure was applied on every effect for which the sphericity assumption was violated. For significant main effects, multiple comparisons tests were performed using the Bonferroni correction.

3.1 Validation time

The time between the notification onset and validation was compared across conditions to determine the salience of designs (Figure 5). Because validation time distribution was positively skewed in each condition, data were log-transformed before performing the ANOVA. The analysis conducted on transformed data showed a significant difference between the five notification types, $F(4,116) = 119.75$, $p < 0.001$. Post-hoc tests revealed that participants were significantly slower to validate Colour and Colour-Blink notifications than they were to acknowledge the Box-Animation, Halo or Shadow-Mask designs (all p-values < 0.001). Moreover, transformed validation times were faster for Halo and Shadow-Mask than for Box-Animation (p-values < 0.04).

We further analysed validation time according to the distance on the screen between the guided plane (primary task) and the notified plane (interruption) in order to verify whether the differences in attentional power between designs were the same at closer distances (18–30 cm, 15–23° of visual angle) as they were at further distances (30–50 cm, >23°). A 2 (distance) × 5 (notification type) repeated-measures ANOVA performed on log-transformed data showed a main effect of distance, $F(1,29) = 6.76$, $p = 0.015$, with transformed validation times being slower for larger distances, but no interaction, $F(4,116) < 1$.

3.2 Eye movements

First, we analysed the time taken from the onset of the notification to when the participant fixated on it (Figure 6). This is seen as the participant's reaction time in terms of the time it takes to identify the target in question. The ANOVA showed a main effect of design, $F(4,116) = 34.54$, $p < 0.001$, with a pattern similar to that of validation time: participants were quicker to notice and fixate the Box-Animation, Halo and Shadow-Mask designs than Colour or Colour-Blink (all p-values < 0.001).

We then compared across designs in terms of time to respond to the notification (click on the label) after it had been fixated. In essence, this is a similar measurement to overall response time (RT) provided in Figure 5 but using eye-tracking data to provide converging evidence. The main effect of notification type was significant, $F(4,116) = 6.94$, $p < 0.001$, because response times for Colour-Blink were slower than for any other design (p-values < 0.035) apart from Colour.

Finally, we measured fixation time (>50 ms) on the alert. Although we cannot unequivocally link fixation time to the cognitive function of comprehending the alert, research into the so-called mind-eye hypothesis provides growing evidence that measures of oculometry can help inform us of underlying mental processes (e.g. Theeuwes, Belopolsky, and Olivers 2009;

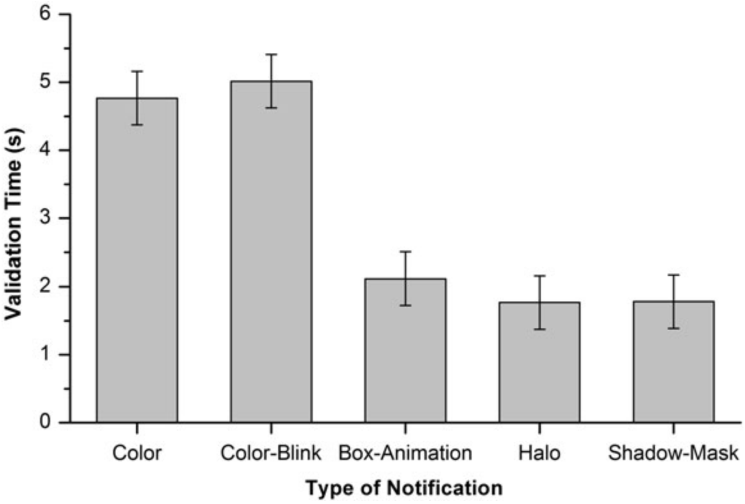

Figure 5. Validation time (in s) for each type of notification. Error bars represent 95% within-participant confidence intervals with Masson and Loftus's (2003) method.

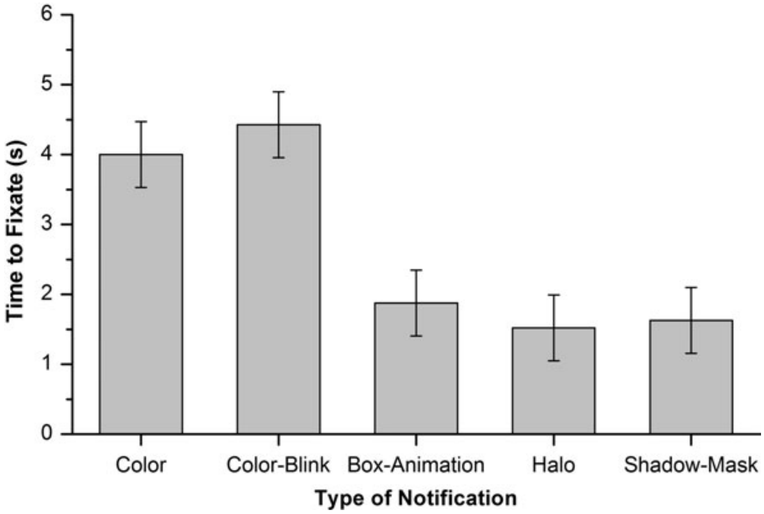

Figure 6. Time (in s) from notification onset until fixation for each type of notification. Error bars represent 95% within-participant confidence intervals with Masson and Loftus's (2003) method.

Tremblay and Saint-Aubin 2009; Vachon and Tremblay 2014). In the current context, we made the assumption that time fixating the alert could be used to provide an indication of the time needed for participants to decide what action to take in order to make a response (Hodgetts, Vachon, and Tremblay 2014; Morrison et al. 1997; Poole and Ball 2006). Since the designs were believed to be equally legible, we expected that fixation time on the alert would not differ as a function of notification type. This was indeed the case and there was no significant difference between designs, $F(4,116) = 2.22$, $p > 0.05$.

3.3 Errors

Errors are the number of missed notifications which were not acknowledged within the time the aircraft spent in the notification zone (on average 19.62 s). Out of the 1200 alerts presented, 20 static Colour notifications and 21 Colour-Blink notifications were not perceived. There were no missed notifications for the other three designs. It is possible that the miss rate may have been even higher if participants had to respond in an even shorter time. However, 95% of alerts were responded to within 6.4 s and so perhaps any longer time was no more beneficial. The number of errors did not differ in accordance with distance: 23 errors were made for notifications appearing at less than 30 cm and 18 errors for those appearing at a distance greater than 30 cm.

3.4 Effect on the primary task

Performance on the primary task (accuracy at entering the required values for the guiding task) was compared across the five design conditions (Figure 7). The range of primary task performance between 75% and 90% could be considered quite low, but this was because instructions prioritised the notification task. Although participants were told to input instructions for the guided plane as quickly and accurately as possible, they were told to validate notifications as soon as they were detected, even if this was before completing a particular entry on the main task (it was specified that it would be possible to validate the notification when the instruction menu was still open). Given the instructions, it is unsurprising that there was a certain decrement to the primary task. However, an 85% performance level does seem acceptable, given that the main task requirements were quite complicated and the task was performed under dual-task conditions. A one-way repeated-measures ANOVA revealed a main effect on performance of notification type, $F(4,116) = 11.91$, $p < 0.001$, and multiple comparisons tests indicated that performance on the primary task was significantly worse in Shadow-Mask than in Colour, Colour-Blink and Box-Animation (p-values < 0.006). Also, performance in Halo was significantly lower than in Colour-Blink and Box-Animation (p-values < 0.002).

3.5 Subjective reports

Participant comments from the debriefing session after the experiment are summarised in Table 1. These subjective reports closely match the objective measures by suggesting that the Colour and Colour-Blink designs are better assimilated into the

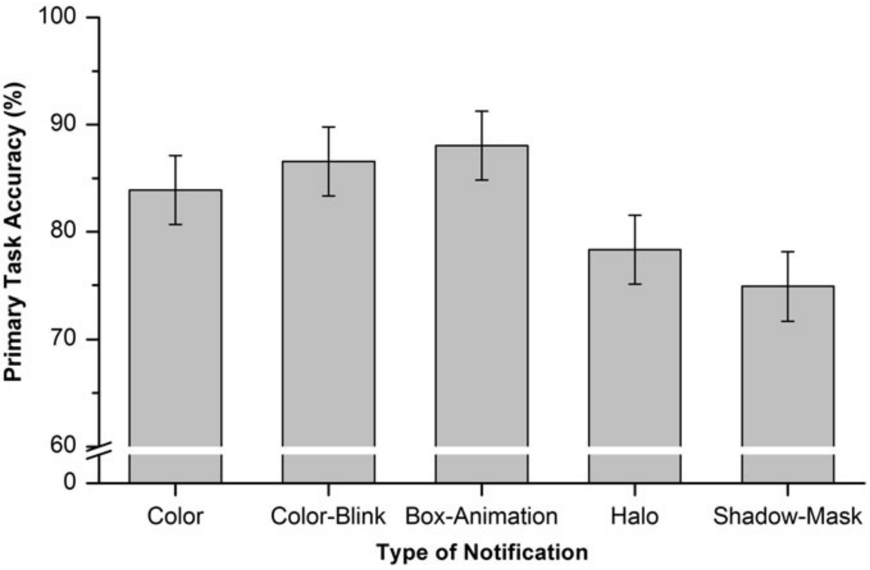

Figure 7. Accuracy level at the primary task (in %) for each type of notification. Error bars represent 95% within-participant confidence intervals with Masson and Loftus's (2003) method.

Table 1. Summary of subjective comments made during debriefing regarding the five different alert types.

	Positive comments	Negative comments
Colour	• Does not interrupt primary task • Red colour attracts attention when visually scanning the screen • Useful for non-urgent alerts	• Alert missed if attention focused on another part of the screen • Only perceived during a visual scan of the screen
Colour-Blink	• Does not interrupt primary task • Blinking red is quite effective (synonymous with danger) • Relevant for non-urgent alerts • Perceived better than Colour (but still insufficient)	• Alert is missed/perception is delayed if attention focused elsewhere on the screen • Only perceived during a visual scan of the screen
Box-Animation	• Not too intrusive, attracts attention just enough • Immediately perceptible without overloading the image • Best compromise between awareness of alert and keeping attention on the primary task • Perceived better than Colour-Blink because it takes up a little more space • In real life it would be the best very short-term solution	• Difficult to look somewhere else while the chevrons are flashing • Slower perception of the alert when at the edge of the screen or far from the plane currently being observed
Halo	• Alert perceived almost instantly • Alert cannot be missed • Attracts attention without being too intrusive/ disruptive	• Loads the screen that already contains a lot of information • Attracts attention too much, too disruptive
Shadow-Mask	• Alert cannot be missed • Interesting idea, but the mask should be less opaque	• Extremely intrusive • Forces interruption of a task that may be more important than the alert • Resuming the primary task is difficult and delayed • Difficult to manage cases of double alerts • The only one of the five alerts that seems unusable in ATC

primary task but could be missed, while Halo and Shadow-Mask are perceived instantly but are perhaps too intrusive. Box-Animation appears clearly as the best compromise for situation awareness in these reports.

4. Discussion

The current experiment tested the feasibility of five different notification designs within an ATC context, taking into account both attentional costs (disruption from overly salient designs) and attentional failures (missed notifications for designs not salient enough). The three animated alerts (Halo, Shadow-Mask and Box-Animation) were perceived quickly and without error. Colour and Colour-Blink fared less well with slower validation times and some notifications going unnoticed in the periphery of vision. However, the attentional power of Halo and Shadow-Mask equally became a disadvantage when taking into account performance on the primary task. This illustrates the need to adopt a holistic approach that considers multiple aspects of an operator's task when introducing new technological solutions.

First and foremost, visual warnings should have the power to capture attention during an ongoing task, alerting the operator to potential concerns elsewhere in the task environment. All alerts were perceived in the three animated design conditions, but operators occasionally suffered inattentional blindness for Colour and Colour-Blink notifications and, furthermore, were on average 3 s ($>100\%$) slower to respond in these conditions. Of course, the acceptable time to respond to an alert depends on the level of criticality of the information involved, but Colour-Blink notifications already correspond to a high level of alert in aviation. Vision research indicates that the colour features of a stimulus do have the capacity to capture attention (e.g. Turatto and Galfano 2000) but this power may be reduced in complex C2 environments with data-rich displays (Nikolic, Orr, and Sarter 2004). Motion is known to be better at capturing attention (Bartram, Ware, and Calvert 2003; McCrickard, Catrambone, and Stasko 2001), and the more animated designs of Halo, Shadow-Mask and Box-Animation suffered no inattentional blindness. When deeply engaged in a demanding task, the operator's functional field of view tends to narrow, making it difficult to extract peripheral information (Chan and Courtney 1993). Inattentional blindness is more likely to occur under conditions of high perceptual load (Cartwright-Finch and Lavie 2007) or increased visuo-spatial memory load (Todd, Fougnie, and Marois 2005) – conditions that characterise ATC operations. Furthermore, it is known that colour perception is degraded as cones become more sparsely distributed with greater eccentricity (Hansen, Pracejus, and Gegenfurtner 2009); as such, alerts that are distinguished in terms of colour are likely to be less effective than when salience is determined by other properties. The current findings are in keeping with the features of the NSEEV model (Steelman, McCarley, and Wickens 2011); that is, alerts were responded to more quickly if they were animated (dynamic salience) and if they made use of foval rather than peripheral vision (eccentricity from gaze). Importantly, the effects of retinal eccentricity and salience on RT were additive; they did not interact (Steelman, McCarley, and Wickens 2013). Further experimentation could determine whether the choice of colour contrast and animation cycle for Colour-Blink could be made more efficient, but it likely remains the case that an operator in a high-load situation could experience cognitive tunnelling and consequently fail to notice even a blinking alert in peripheral vision.

The second issue for notification design is that although it should capture attention, this should not be to the detriment of other task elements. For Halo and Shadow-Mask, perception was almost immediate but their intrusive nature was equally a disadvantage in terms of performance on the ongoing ATC task. For Halo, attention naturally focuses on the area highlighted by the concentric circles, but this is costly in visually loading an image that already contains a lot of information. When sometimes it may be necessary to delay response to an alert – because the factors associated with the current situation are deemed to be of higher priority – the initiated warning will continue in the background and may become a source of visual distraction that compromises a task of potentially greater importance. In the auditory domain, low-level warnings can be detrimental to high-priority tasks (Banbury et al. 2003), which may result in complications more serious than those triggered by the original alert. For Shadow-Mask, attention is automatically directed to the visual warning because all other information on the screen is darkened. It therefore demands immediate attention, but interruptions have been shown to impair situation awareness in C2 situations (Hodgetts, Vachon, and Tremblay 2014) and may be particularly disruptive if there is no opportunity to consolidate features of the primary task before switching (Hodgetts and Jones 2006). Thus, inline with our holistic approach, we find that designs with quicker perception times come with impaired performance on the primary task. Moreover, our subjective measures were consistent with the empirical findings, that the Halo and Shadow-Mask alerts were impossible to miss but very disruptive to performance of the ATC task. These two designs would also raise problems in the case of multiple alerts, disrupting the primary task and decreasing the effectiveness of the alert.

Using the CSE perspective of a joint cognitive system, technology should team with the operator to optimise performance of the human–machine system without incurring costs in other domains. We find therefore that the Box-Animation design best achieves a balance between attentional costs and failures. It was very noticeable even in situations of high load, but not so intrusive that primary task performance suffered. Unlike Colour-Blink, the animation occurs outside of the label and so the field of vision is wider, making it more likely that the alert is perceived quickly. It also has the advantage over Halo and Shadow-Mask in that it does not overload the main display or force the operator to switch away from the primary task beyond their control, and thus seems to deliver notifications in an optimal fashion.

Rather than dismiss the Halo and Shadow-Mask designs entirely, we should consider their use in emergency situations of the highest order (e.g. imminent plane crash), when it may be necessary to engage radical methods of alerting to ensure that action is taken immediately, for example in the case of attentional tunnelling (Wickens and Alexander 2009). Halo is a very prominent design, but in particular Shadow-Mask is impossible not to perceive as the overall display is significantly degraded in order to draw attention to the notified object (see Dehais, Causse, and Tremblay 2011). Importantly, the type of alert should be appropriate for the severity of the situation that it relates to. Operators are less likely to attend to notifications that occur frequently and have a high incidence of false alarms (Wickens and Colcombe 2007), so in highly critical situations the alert must be increasingly salient and rarely experienced.

5. Practical applications

In designing notifications, it is necessary to achieve a balance between the attentional power of the design and its relative importance in the task context. The present study suggests that the usability of current operational designs in ATC should be reassessed: the fact that even the high-priority animated alert was occasionally missed in peripheral vision is a major concern given the high-risk nature of ATC operations. Furthermore, these two operational designs did not differ significantly in salience, thus coming into conflict with operational need (one should be more attention-grabbing than the other). Perhaps, both types of notification should therefore be considered more appropriate as markers or low-level warnings than as a higher-level alert. The prototype designs were much more effective due to the use of movement, although there was no order of saliency established between them; it was their effect on the primary task that allowed us to distinguish a preferred design. Quantitative data and qualitative reports demonstrated that the Box-Animation alert would effectively convey its immediacy, but without depriving the controller of the rest of the current air situation. It thus seems the best option to incorporate two seemingly incompatible requirements.

We reflect on those points stemming from the study that could be used to make more general recommendations for notification design. The best compromise, Box-Animation, involved the use of both colour and movement – two factors that are already known to be useful in capturing attention. Box-Animation used the colour yellow which is known to be better perceived in the periphery than the red used for Colour and Colour-Blink (Hansen, Pracejus, and Gegenfurtner 2009). The type of animation is important though too, and blinking coloured text was not as successful at capturing attention as the pulsating nature of the chevrons. While Colour-Blink only involved the animation of a small part of the text on the label (e.g. the flight level), leaving much of the label unchanged, the chevrons pulsated around the outside of the whole label and so occupied a much larger area. Furthermore, the animation used for Colour-Blink was a much smoother on/off alternation, whereas the slow in/slow out used for Box-Animation made the chevrons appear to shrink inwards and then ‘pop’ back out in a jerking-type movement. Although this is a repeated movement and therefore not entirely unexpected, the irregular popping action has a ‘deviant’ quality that captures attention and is difficult to ignore, rather like the way in which a deviant auditory stimulus can capture attention among general background sound (Hughes, Vachon, and Jones 2005). On a radar screen that already contains various dynamically moving objects, movement in itself is not enough to guarantee attentional capture; for a warning signal, the type of movement used must be demanding of attention. Together with the choice of colour, these two factors – the size of the animated area and the change in velocity of the animation – seem to be critical in establishing greater salience. Equally, the benefit of Box-Animation was that the animation was not too disruptive so as to impair the primary task. Unlike Halo or Shadow-Mask that dominated the whole screen, Box-Animation was centred on the specific label of the notified aircraft, allowing participants greater choice over when to switch tasks rather than it being imposed upon them. Therefore, in order to ensure this optimal point on the salience continuum, designers may do well to restrict any animation to the confines of the specific aircraft label.

Despite the very intrusive nature of Halo and Shadow-Mask, there may too be a place for these alerts in ATC. For example, in some en-route ATC centres in France, controllers delivering air traffic onto another sector are able to pan their radar image towards an onward area but at the cost of a different part of their sector no longer being visible on the screen. Controllers anticipate the flow of aircraft in advance and shift the radar image as is necessary to facilitate the sequencing and delivery of aircraft onto the next sector. However, one should consider the circumstance that an alarm for the controller’s current sector could be triggered but go unnoticed due to the image shift; in this scenario, even the attention-capturing properties of a Box-Animation alert would be futile if the aircraft to which it related was not currently displayed on the screen. A Halo alert, however, would be able to convey the fact that critical information was in need of attention in the obscured area of the radar screen.

In cases of absolute emergency, there may also be a place for the highly intrusive Shadow-Mask alert; however, forcing a change of activity beyond the user’s control should be considered carefully. An alert so intrusive should only be used as a last resort when disruption to the ongoing task is judged imperative. In terms of aviation, however, in a situation of imminent collision – which is perhaps the only absolute emergency that would justify such cognitive countermeasures – one might argue that there is no place for the air traffic controller as the automated onboard Traffic Collision Avoidance System (TCAS) system is the ultimate tool that would seize control of the situation. A ground-based system perhaps cannot afford to be too intrusive because the potential emergency would not yet be sufficiently imminent to completely overshadow the monitoring of all other aircraft in the vicinity. Moreover, one could argue that it should then be the operator – and not an automated system – who decides how to manage the priority of these tasks, and that he/she should not be forced to deal with the intruding alert immediately and without forewarning, at the expense of everything else. In such a complex and high-risk setting as aviation, the operator can ill afford to lose visual access to the main radar display for the sake of a single alert. However, it may be important for ATC to have a warning system, similar to cognitive countermeasures, that is activated several tens of seconds before TCAS so that the operator can attempt to resolve the situation before the need for TCAS. This is especially important given that a lack of faith in automation may lead some pilots to ignore the automated TCAS system, and instead place more value upon 'human' instructions from the controller. In any event, exceptionally strict trigger conditions would need to be in place so as to avoid false alarms that could compromise safety in an otherwise non-emergency situation.

Methodologically, we have demonstrated the use of the LABY microworld as an ideal experimental platform for the evaluation of ATC innovations, as it provides an optimal balance between ecological validity and experimental control. Of course, there are several dimensions of the current testing paradigm which do not perfectly reflect the real world. For example, participants were exposed to alerts much more frequently than controllers in a normal operational situation, although we would still expect the same type of effects to occur. Furthermore, the experiment only lasted 20 minutes, while controllers would generally be working for many hours a day. It is possible that learning/sensitivity may improve over time as participants become more familiar with the microworld and the types of alerts. Equally though, operator performance may decrease over time due to a vigilance decrement, and these may be interesting points for future research. At a more advanced stage, it would be necessary to validate the effects obtained with LABY in a more complex simulation and an operational setting.

The current study illustrates the importance of a holistic approach when conducting such evaluations of new systems or support tools. Rather than focusing on a single variable of interest directly associated with the main purpose of the experiment (e.g. notification validation time), our novel approach used several concurrent measurements to gain a broader view of the effect that each design might have on overall performance. A specific benefit on one dimension may be accompanied by a detriment on another; for example, intrusive designs are perceived more quickly, but incur a cost to the ongoing task. A holistic approach should therefore be used to ensure that the implementation of any new system is truly beneficial in all aspects (Lafond et al. 2010).

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References

Ancman, E. 1991. "Peripherally Located CRTs: Color Perception Limitations." In *Proceedings of the IEEE National Aerospace and Electronics Conference*, 960–965. New York: Institute of Electrical and Electronics Engineers.

Athènes, S., S. Chatty, and A. Bustico. 2000. "Human Factors in ATC Alarms and Notifications Design: An Experimental Evaluation." *Proceedings of the ATM'2000 R&D Seminar, 2000*, atmseminar.org.

Bailey, B. P., J. A. Konstan, and J. V. Carlis. 2001. "The Effects of Interruptions on Task Performance, Annoyance, and Anxiety in the User Interface." In *Human–Computer Interaction – INTERACT 2001 Conference Proceedings*, edited by M. Hirose, 593–601. Amsterdam: IOS.

Banbury, S., L. Fricker, S. Tremblay, and L. Emery. 2003. "Using Auditory Streaming to Reduce Disruption to Serial Memory by Extraneous Auditory Warnings." *Journal of Experimental Psychology: Applied* 9: 12–22.

Bartram, L., C. Ware, and T. Calvert. 2001. "Moving Icons: Detection and Distraction." *Proceedings of the IFIP TC.13 International Conference on Human–Computer Interaction (INTERACT 2001)*, Tokyo.

Bartram, L., C. Ware, and T. Calvert. 2003. "Moticons: Detection, Distraction and Task." *International Journal of Human-Computer Studies* 58: 515–545.

Bauer, B., P. Jolicœur, and W. B. Cowan. 1996. "Visual Search for Colour Targets That Are or Are Not Linearly Separable from Distractors." *Vision Research* 36: 1439–1466.

Beringer, D. B., and H. C. Harris Jr. 1999. “Automation in General Aviation: Two Studies of Pilot Responses to Autopilot Malfunctions.” *International Journal of Aviation Psychology* 9: 155–174.

Breznitz, S. 1983. *Cry Wolf: The Psychology of False Alarms*. Hillsdale, NJ: Lawrence Erlbaum.

Cartwright-Finch, U., and N. Lavie. 2007. “The Role of Perceptual Load in Inattentional Blindness.” *Cognition* 102: 321–340.

Chan, H. S., and A. J. Courtney. 1993. “Effects of Cognitive Foveal Load on a Peripheral Single-Target Detection Task.” *Perceptual and Motor Skills* 77: 515–533.

Crebolder, J. M. 2012. “Investigating Visual Alerting in Complex Command and Control Environments.” *Journal of Human Performance in Extreme Environments* 10. doi:10.7771/2327-2937.1000.

Dehais, F., M. Causse, and S. Tremblay. 2011. “Mitigation of Conflicts with Automation: Use of Cognitive Countermeasures.” *Human Factors* 53: 448–460.

Dehais, F., M. Causse, F. Vachon, and S. Tremblay. 2012. “Cognitive Conflict in Human-Automation Interactions: A Psychophysiological Study.” *Applied Ergonomics* 43: 588–595.

Dehais, F., C. Tessier, L. Christophe, and F. Reuzeau. 2010. “The Perseveration Syndrome in the Pilot’s Activity: Guidelines and Cognitive Countermeasures.” *Human Error, Safety and Systems Development. Lecture Notes in Computer Science* 5962: 68–80.

Drew, T., M. L. -H. Võ, and J. M. Wolfe. 2013. “The Invisible Gorilla Strikes Again: Sustained Inattentional Blindness in Expert Observers.” *Psychological Science* 24: 1848–1853.

Drieghe, D., K. Rayner, and A. Pollatsek. 2005. “Eye Movements and Word Skipping during Reading Revisited.” *Journal of Experimental Psychology: Human Perception and Performance* 31: 954–969.

Duchowski, A. T. 2007. *Eye Tracking Methodology: Theory and Practice*. 2nd ed. London: Springer.

Durlach, P. J., J. P. Kring, and L. D. Bowens. 2009. “Effects of Action Video Game Experience on Change Detection.” *Military Psychology* 21: 24–39.

D’Zmura, M. 1991. “Color in Visual Search.” *Vision Research* 31: 951–966.

Faraday, P., and A. Sutcliffe. 1997. “Designing Effective Multimedia Presentations.” In *Proceedings of ACM CHI ’97*, 272–279. New York: ACM.

Fougnie, D., and R. Marois. 2007. “Executive Working Memory Load Induces Inattentional Blindness.” *Psychonomic Bulletin & Review* 14: 142–147.

Franconeri, S. L., A. Hollingworth, and D. J. Simons. 2005. “Do New Objects Capture Attention?” *Psychological Science* 16 (4): 275–281.

Hansen, T., L. Pracejus, and K. R. Gegenfurtner. 2009. “Color Perception in the Intermediate Periphery of the Visual Field.” *Journal of Vision* 9: 1–12. doi:10.1167/9.4.26.

Hodgetts, H. M., and D. M. Jones. 2006. “Contextual Cues Aid Recovery from Interruption: The Role of Associative Activation.” *Journal of Experimental Psychology: Learning, Memory & Cognition* 35: 1120–1132.

Hodgetts, H. M., F. Vachon, and S. Tremblay. 2014. “Background Sound Impairs Interruption Recovery in Dynamic Task Situations: Procedural Conflict?” *Applied Cognitive Psychology* 28: 10–21.

Hoffman, J. E. 1998. “Visual Attention and Eye Movements.” In *Attention*, edited by H. Pashler, 119–154. London: University College London Press.

Hughes, R. W., F. Vachon, and D. M. Jones. 2005. “Auditory Attentional Capture during Serial Recall: Violations at Encoding of an Algorithm Based Neural Model?” *Journal of Experimental Psychology: Learning, Memory, and Cognition* 31: 736–749.

Iani, C., and C. D. Wickens. 2007. “Factors Affecting Task Management in Aviation.” *Human Factors* 49: 16–24.

Imbert, J. -P., H. M. Hodgetts, R. Parise, F. Vachon, and S. Tremblay. Forthcoming. “The LABY Microworld: A Platform for Research, System Engineering, and Training in Air Traffic Control.” *Proceedings of the Human Factors and Ergonomics Society 58th Annual Meeting*.

Itti, L., and C. Koch. 2000. “A Saliency-Based Search Mechanism for Overt and Covert Shifts of Visual Attention.” *Vision Research* 40: 1489–1506.

Jonides, J. 1981. “Voluntary versus Automatic Control over the Mind’s Eye’s Movement.” In *Attention and Performance IX*, edited by J. B. Long, and A. D. Baddeley, 187–203. Hillsdale, NJ: Lawrence Erlbaum.

Lafond, D., F. Vachon, R. Rousseau, and S. Tremblay. 2010. “A Cognitive and Holistic Approach to Developing Metrics for Decision Support in Command and Control.” In *Advances in Cognitive Ergonomics*, edited by D. B. Kaber, and G. Boy, 65–73. Danvers, MA: CRC Press.

Loft, S., R. E. Smith, and A. Bhaskara. 2011. “Prospective Memory in an Air Traffic Control Simulation: External Aids That Signal When to Act.” *Journal of Experimental Psychology: Applied* 17: 60–70.

Mack, A., and I. Rock. 1998. *Inattentional Blindness*. Cambridge, MA: MIT Press.

Maglio, P. P., and C. S. Campbell. 2000. “Tradeoffs in Displaying Peripheral Information.” In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI ’00)*, 241–248. New York: ACM.

Masson, M. E. J., and G. R. Loftus. 2003. “Using Confidence Intervals for Graphically Based Data Interpretation.” *Canadian Journal of Experimental Psychology* 57: 203–220.

McCrickard, D. S., R. Catrambone, C. M. Chewar, and J. T. Stasko. 2003. “Establishing Tradeoffs That Leverage Attention for Utility: Empirically Evaluating Information Display in Notification Systems.” *International Journal of Human-Computer Studies* 58: 547–582.

McCrickard, D. S., R. Catrambone, and J. T. Stasko. 2001. “Evaluating Animation in the Periphery as a Mechanism for Maintaining Awareness.” *Proceedings of the IFIP TC.13 International Conference on Human–Computer Interaction (INTERACT 2001)*, Tokyo, 148–156.

McCrickard, D. S., and C. M. Chewar. 2003. “Attuning Notification Design to User Goals and Attention Costs.” *Communications of the ACM* 46 (3): 67–72.

Miyamae, M. 2008. "Design Guidelines of a Context-Aware Notification System for Nursing: Pervasive Computing Technologies for Healthcare." *Pervasive Health 2008*.

Morrison, J. G., S. P. Marshall, R. T. Kelly, and R. A. Moore. 1997. "Eye Tracking in Tactical Decision Making Environments: Implications for Decision Support Evaluation." *Third International Command and Control Research and Technology Symposium*, National Defense University, June 17–20.

Most, S. B., B. J. Scholl, E. Clifford, and D. J. Simons. 2005. "What You See Is What You Set: Sustained Inattentional Blindness and the Capture of Awareness." *Psychological Review* 112: 217–242.

Most, S. B., D. J. Simons, B. J. Scholl, and C. F. Chabris. 2000. "Sustained Inattentional Blindness: The Role of Location in the Detection of Unexpected Dynamic Events." *Psyche* 6 (14): http://www.theassc.org/files/assc/2471.pdf

Navon, D., and D. Gopher. 1979. "On the Economy of the Human-Processing System." *Psychological Review* 86: 214–255. doi:10.1037/0033-295X.86.3.214.

Newby, E. A., and I. Rock. 1998. "Inattentional Blindness as a Function of Proximity to the Focus of Attention." *Perception* 27: 1025–1040.

Nikolic, M. I., J. M. Orr, and N. B. Sarter. 2004. "Why Pilots Miss the Green Box: How Display Context Undermines Attention Capture." *The International Journal of Aviation Psychology* 14 (1): 39–52.

Nikolic, M. I., and N. B. Sarter. 2001. "Peripheral Visual Feedback: A Powerful Means of Supporting Attention Allocation and Human-Automation Coordination in Highly Dynamic Data-Rich Environments." *Human Factors* 43: 30–38.

Pearson, D., and A. Sahraie. 2003. "Oculomotor Control and the Maintenance of Spatially and Temporally Distributed Events in Visuo-Spatial Working Memory." *The Quarterly Journal of Experimental Psychology Section A: Human Experimental Psychology* 56: 1089–1111.

Poole, A., and L. J. Ball. 2006. "Eye Tracking in Human-Computer Interaction and Usability Research: Current Status and Future Prospects." In *Encyclopedia of Human Computer Interaction*, edited by C. Ghaoui, 211–219. Hershey, PA: Idea Group.

Reason, J. T. 1990. *Human Error*. New York: Cambridge University Press.

Remington, R. W., J. C. Johnston, and S. Yantis. 1992. "Involuntary Attentional Capture by Abrupt Onsets." *Perception & Psychophysics* 51: 279–290.

Sarter, N. B., and D. D. Woods. 1994. "Pilot Interaction with Cockpit Automation II: An Experimental Study of Pilots' Model and Awareness of the Flight Management System (FMS)." *International Journal of Aviation Psychology* 4: 1–28.

Simons, D. J., and C. F. Chabris. 1999. "Gorillas in Our Midst: Sustained Inattentional Blindness for Dynamic Events." *Perception* 28: 1059–1074.

St. John, M., H. S. Smallman, and D. I. Manes. 2005. "Recovery from Interruptions to a Dynamic Monitoring Task: The Beguiling Utility of Instant Replay." In *Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting*, 473–477. Santa Monica, CA: Human Factors and Ergonomics Society.

Steelman, K. S., J. S. McCarley, and C. D. Wickens. 2011. "Modeling the Control of Attention in Visual Workspaces." *Human Factors* 53: 142–153. doi:10.1177/0018720811404026.

Steelman, K. S., J. S. McCarley, and C. D. Wickens. 2013. "Great Expectations: Top-Down Attentional Control Modulates the Costs of the Clutter and Eccentricity on Alert Detection Performance." *Journal of Experimental Psychology: Applied* 19: 403–419. doi:10.1037/a0034546.

Stelzer, E. M., and C. D. Wickens. 2006. "Pilots Strategically Compensate for Display Enlargements in Surveillance and Flight Control Tasks." *Human Factors* 48: 166–181.

Theeuwes, J. 1991. "Exogenous and Endogenous Control of Attention: The Effects of Visual Onsets and Offsets." *Perception and Psychophysics* 49: 83–90.

Theeuwes, J., A. Belopolsky, and C. N. L. Olivers. 2009. "Interactions between Working Memory, Attention and Eye Movements." *Acta Psychologica* 132: 106–114.

Todd, J. J., D. Fougnie, and R. Marois. 2005. "Visual Short-Term Memory Load Suppresses Temporo-Parietal Junction Activity and Induces Inattentional Blindness." *Psychological Science* 16: 965–972.

Trafton, J. G., E. M. Altmann, D. P. Brock, and F. E. Mintz. 2003. "Preparing to Resume an Interrupted Task: Effects of Prospective Goal Encoding and Retrospective Rehearsal." *International Journal of Human Computer Studies* 58: 582–602.

Tremblay, S., and J. Saint-Aubin. 2009. "Evidence of Anticipatory Eye Movements in the Spatial Hebb Repetition Effect: Insights for Modeling Sequence Learning." *Journal of Experimental Psychology: Learning, Memory and Cognition* 35: 1256–1265.

Turatto, M., and G. Galfano. 2000. "Color, Form and Luminance Capture Attention in Visual Search." *Vision Research* 40: 1639–1643.

Vachon, F., and S. Tremblay. 2014. "What Eye Tracking Can Reveal about Dynamic Decision-Making." *Proceedings of the 5th International Conference on Applied Human Factors and Ergonomics AHFE 2014*, edited by T. Ahram, W. Karwowski and T. Marek, Kraków, Poland.

Vachon, F., B. R. Vallières, D. M. Jones, and S. Tremblay. 2012. "Nonexplicit Change Detection in Complex Dynamic Settings: What Eye Movements Reveal." *Human Factors* 54: 996–1007.

Ware, C., J. Bonner, R. Cater, and W. Knight. 1992. "Simple Animation as a Human Interrupt." *International Journal of Human-Computer Interaction* 4: 341–348.

Wickens, C. D. 1980. "The Structure of Attentional Resources." In *Attention and Performance VIII*, edited by R. Nickerson, 239–257. Hillsdale, NJ: Lawrence Erlbaum.

Wickens, C. D., and A. L. Alexander. 2009. "Attentional Tunneling and Task Management in Synthetic Vision Displays." *The International Journal of Aviation Psychology* 19: 182–199.

Wickens, C., and A. Colcombe. 2007. "Dual-Task Performance Consequences of Imperfect Alerting Associated with a Cockpit Display of Traffic Information." *Human Factors* 49: 839–850.

Wickens, C. D., B. L. Hooey, B. F. Gore, A. Sebok, and C. S. Koenicke. 2009a. "Identifying Black Swans in NextGen: Predicting Human Performance in Off-Nominal Conditions." *Human Factors* 51: 638–651.

Wickens, C. D., S. Rice, D. Keller, S. Hutchins, J. Hughes, and K. Clayton. 2009b. “False Alerts in Air Traffic Control Conflict Alerting System: Is There a ‘Cry Wolf’ Effect?” *Human Factors* 51: 446–462. doi:10.1177/0018720809344720.

Yantis, S., and J. Jonides. 1990. “Abrupt Visual Onsets and Selective Attention: Voluntary versus Automatic Allocation.” *Journal of Experimental Psychology: Human Perception and Performance* 16: 121–134.

Yantis, S., and J. Jonides. 1996. “Attentional Capture by Abrupt Onsets: New Perceptual Objects or Visual Masking?” *Journal of Experimental Psychology: Human Perception and Performance* 22 (6): 1505–1513.

Zelinsky, G. J. 2008. “A Theory of Eye Movements during Target Acquisition.” *Psychological Review* 115: 787–835.