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RUNNING HEAD: Notification design and Attentional failures

Attentional costs and failures in air traffic control notifications

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Abstract

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 color, 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.

Keywords: Air traffic control, Visual notifications, Attentional capture, Detection, Eye movement

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.

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 healthcare, 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 optimize 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, Vachon, Rousseau, & Tremblay, 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, & 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 & Gopher, 1979; Wickens, 1980). Using an 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. One way to provide information on large or multiple screens, while minimizing 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 ($0-2^\circ$), para-foveal area ($2^\circ-5^\circ$), and the area of peripheral vision ($>5^\circ$). In operational control centers, 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 center of vision, parameters such as color, motion, luminance, opacity, size, time profile and frequency of the signal events should be taken into account in terms of notification design (Athènes, Chatty, & Bustico, 2000).

In ATC, on-screen notifications generally rely on color to alert the controller to abnormal or risk conditions. In peripheral vision, the choice of color in particular is crucial because perception is not uniform, for example, green is very badly perceived at 30° from the center 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 which 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 & 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 color similarity between the target and the background, and the movement of other background elements (Nikolic, Orr, & Sarter, 2004). Motion is better detected in the periphery than color or shape cues (Bartram, Ware, & 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, & Calvert, 2003; McCrickard, Catrambone, Chewar, & Stasko, 2003; McCrickard, Catrambone, & Stasko, 2001; Ware, Bonner, Cater, & Knight, 1992). Visual alerting has been studied in command and control (C2) environments specifically, such as pilot in-the-loop flight simulations (Iani & Wickens, 2007; Nikolic & Sarter, 2001; Stelzer & Wickens, 2006), ATC environments (Loft, Smith, & Bhaskara, 2011), and tactical categorisation tasks (Crebolder, 2012). Guidelines have been proposed for designing animated visual signals (Athènes et al., 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, & 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 *saliency* of the item of interest, both static (Itti & Koch, 2000) and dynamic saliency (Yantis & 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 saliency); 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 et al., 2011; Wickens, Hooey, Gore, Sebok, & Koenicke, 2009). 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, & Wolfe, 2013). This phenomenon of inattention blindness (Mack & Rock, 1998; Most, Scholl, Clifford, & Simons, 2005) can occur even when a stimulus is salient in terms of its colour or movement (Mack & Rock, 1998), thus posing a challenge for the design of safety-critical emergency alerts. The likelihood of inattention blindness is increased with the attentional demands of the task (Simons & Chabris, 1999), working memory load (Fougnie & Marois, 2007), the need to maintain information in visuo-spatial memory (Todd, Fougnie, & Marois, 2005), **low expectancy of events (Steelman, McCarley & Wickens, 2013)**, and during periods of high tempo activity with competing visual demands (Nikolic & Sarter, 2001; Sarter & 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, & Bowens, 2009); in fact, operators may even look directly at a critical change but not 'see' it (e.g., Vachon, Vallières, Jones, & Tremblay, 2012). An object is more likely detected if near the focus of visuospatial attention (Most, Simons, Scholl, & Chabris, 2000), but proximity is not sufficient for detection and it can still be missed (Newby & Rock, 1998; Simons & Chabris, 1999). In demanding tasks, operators may experience attentional narrowing or 'tunnelling' (Chan & Courtney, 1993; Wickens & 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, Tessier, Christophe, & Reuzeau, 2010). If operators in these situations do not perceive warnings provided (Beringer & Harris, 1999; Dehais, Causse, Vachon, & Tremblay, 2012; Dehais et al., 2010), 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 et al., 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; although see Wickens, Rice, Keller, Hutchins, Hughes, & Clayton, 2009).

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, & Cowan, 1996; D'Zmura, 1991), luminance (Turatto & Galfano, 2000), motion (Faraday & Sutcliffe, 1997), or the onset of a new object (Remington, Johnston, & Yantis, 1992; Yantis & Jonides, 1996; although see Franconeri, Hollingworth, & 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 et al., 2001), increased task decision-making times (Hodgetts, Vachon, & Tremblay, 2014), and reduced situation awareness (St. John, Smallman, & 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 & Jones, 2006; Trafton, Altmann, Brock, & Mintz, 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 & Campbell, 2000; McCrickard & 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, & 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 characterize 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 & 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, Hodgetts, Parise, Vachon, & Tremblay, 2014) 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 colored text) and high-level alert (blinking colored text), and one is a prototype implemented on a new radar display within the framework of 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 inattentive blindness by capturing attention in foveal vision.

Figure 1

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 foveal 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 tradeoff between alerting task noticeability and ongoing task performance.

2. Method

2.1 Participants

Thirty ATC specialists working for the French civil aviation research center (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 CFL (cleared flight level; 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 CFL and Direct orders was 3.09s (variance 0.7s), while the mean time available for entering orders (mean length of route sections) was 9.14s (variance 7.07s).

Figure 2

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 18.75cm from the guided plane (15 ° at a viewing distance of 70cm). A notification (40 in total; 8 x 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 19.62s (variance 3.1s). 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 whilst there was no notification was on the screen.

2.3 Types of notification

- 1) *Color* is a static notification that displays the word "FNIV" in an orange-red color.

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) *Color-Blink* is colored 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 Color and Color-blink have been operational since 1999.

Figure 3

3) *Box-Animation* involves the same colored 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 program (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, & 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.

Figure 4

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: 18.75cm to 30 cm, or greater than 30cm (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 color perception; 15° to 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 9 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) centered 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, $F(4,116)=119.75, p<.001$. Post-hoc tests revealed that participants were significantly slower to validate Color and Color-Blink notifications than they were to acknowledge the Box-Animation, Halo or Shadow-Mask designs (all $ps<.001$). Moreover, transformed validation times were faster for Halo and Shadow-Mask than for Box-Animation ($ps <.04$).

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, $F(1,29)=6.76, p=.015$, with transformed validation times being slower for larger distances, but no interaction, $F(4,116)<1$.

Figure 5.

3.2 Eye movements

First we analyzed 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, $F(4,116)=34.54, p<.001$), 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 Color or Color-Blink (all $ps<.001$).

Figure 6

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 RT provided in Figure 5 but using eyetracking data to provide converging evidence. The main effect of notification type was significant, $F(4,116)=6.94, p<.001$, because response times for Color-Blink were slower than for any other design ($ps<.035$) apart from Color.

Finally we measured fixation time ($>50ms$) 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, & Olivers, 2009; Tremblay & Saint-Aubin, 2009; Vachon & 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 (Morrison, Marshall, Kelly, & Moore, 1997; Hodgetts et al., 2014; Poole & 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, $F(4,116)=2.22, p>.05$).**

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 1,200 alerts presented, 20 static Color notifications and 21 Color-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 sec 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 30cm, and 18 errors for those appearing at a distance greater than 30cm.

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, $F(4,116)=11.91, p<.001$, and multiple comparisons tests indicated that performance on the primary task was significantly worse in Shadow-Mask than in Color, Color-Blink and Box-

Animation ($ps < .006$). Also, performance in Halo was significantly lower than in Color-Blink and Box-Animation ($ps < .002$).

Figure 7

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 Color and Color-Blink designs are better assimilated into the 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.

-- Table 1 --

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. Color and Color-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 inattention blindness for Color and Color-Blink notifications and furthermore, were on average 3 seconds (>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 Color-Blink notifications already correspond to a high level of alert in aviation. Vision research indicates that the color features of a stimulus do have the capacity to capture attention (e.g., Turatto & Galfano, 2000) but this power may be reduced in complex C2 environments with data-rich displays (Nikolic et al., 2004). Motion is known to be better at capturing attention (Bartram et al., 2003; McCrickard et al., 2001), and the more animated designs of Halo, Shadow-Mask, and Box-Animation suffered no inattention 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 & Courtney, 1993). Inattention blindness is more likely to occur under conditions of high perceptual load (Cartwright-Finch & Lavie, 2007) or increased visuo-spatial memory load (Todd et al., 2005); conditions that characterise ATC operations. Furthermore, it is known that color perception is degraded as cones become more sparsely distributed with greater eccentricity (Hansen, Pracejus, & Gegenfurtner, 2009); as such, alerts that are distinguished in terms of color 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 et al., 2011); that is, alerts were responded to more quickly if they were animated (dynamic salience), and if they made use of foveal 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, & Wickens, 2013).** Further experimentation could determine whether

the choice of color contrast and animation cycle for Color-Blink could be made more efficient, but it likely remains the case that an operator in a high-load situation could experience cognitive tunneling 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, Fricker, Tremblay, & Emery, 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 et al., 2014), and may be particularly disruptive if there is no opportunity to consolidate features of the primary task before switching (Hodgetts & 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 optimize 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 Color-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 & 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 et al., 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 & 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 color and movement – two factors that are already known to be useful in capturing attention. Box-Animation used the color yellow which is known to be better perceived in the periphery than the red used for Color and Color-Blink (Hansen et al., 2009). The type of animation is important though too, and blinking colored text was not as successful at capturing attention as the pulsating nature of the chevrons. While Color-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 Color-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 amongst general background sound (Hughes, Vachon, & 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 color, 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 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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Table 1. *Summary of subjective comments made during debriefing regarding the five different alert types.*

	Positive comments	Negative comments
Color	<ul style="list-style-type: none"> • Does not interrupt primary task • Red color attracts attention when visually scanning the screen • Useful for non-urgent alerts 	<ul style="list-style-type: none"> • Alert missed if attention focused on another part of the screen • Only perceived during a visual scan of the screen
Color-Blink	<ul style="list-style-type: none"> • Does not interrupt primary task • Blinking red is quite effective (synonymous with danger) • Relevant for non-urgent alerts • Perceived better than COLOR (but still insufficient) 	<ul style="list-style-type: none"> • Alert is missed/perception is delayed if attention focused elsewhere on the screen • Only perceived during a visual scan of the screen
Box-Animation	<ul style="list-style-type: none"> • 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 COLORBLINK because it takes up a little more space • "In real life it would be the best very short-term solution" 	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • Alert perceived almost instantly • Alert cannot be missed • Attracts attention without being too intrusive/disruptive 	<ul style="list-style-type: none"> • Loads the screen that already contains a lot of information • Attracts attention too much, too disruptive
Shadow-Mask	<ul style="list-style-type: none"> • Alert cannot be missed • Interesting idea, but the mask should be less opaque 	<ul style="list-style-type: none"> • 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"

Figure captions

Figure 1. The LABY microworld

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

Figure 3. Notifications: (a) Color (b) Color-Blink (c) Box-Animation (d) Shadow-mask

Figure 4. Halo notification

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.

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.

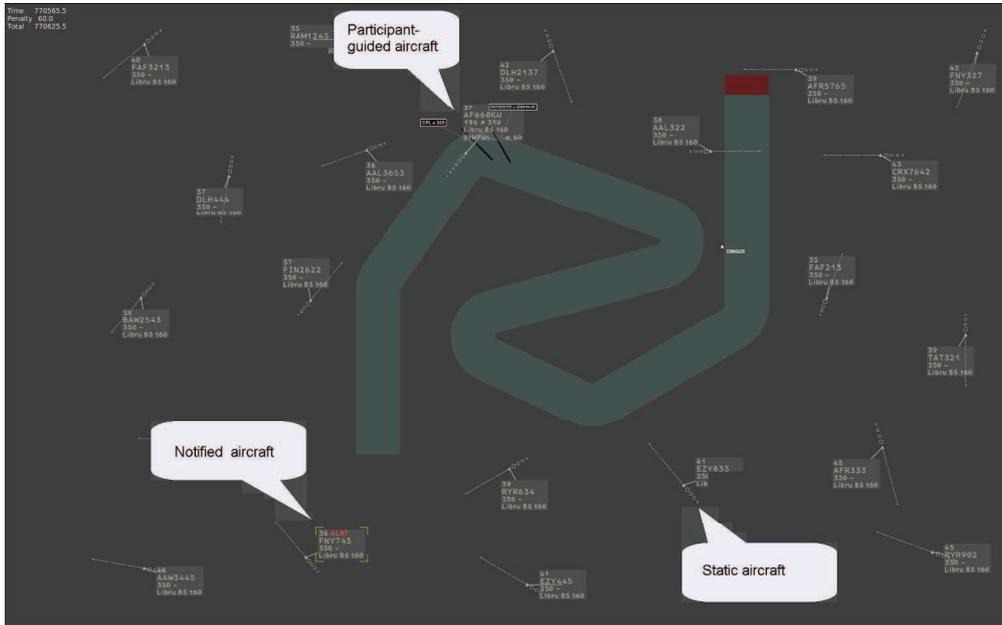


Figure 1. The LABY microworld
677x423mm (96 x 96 DPI)

Review Only

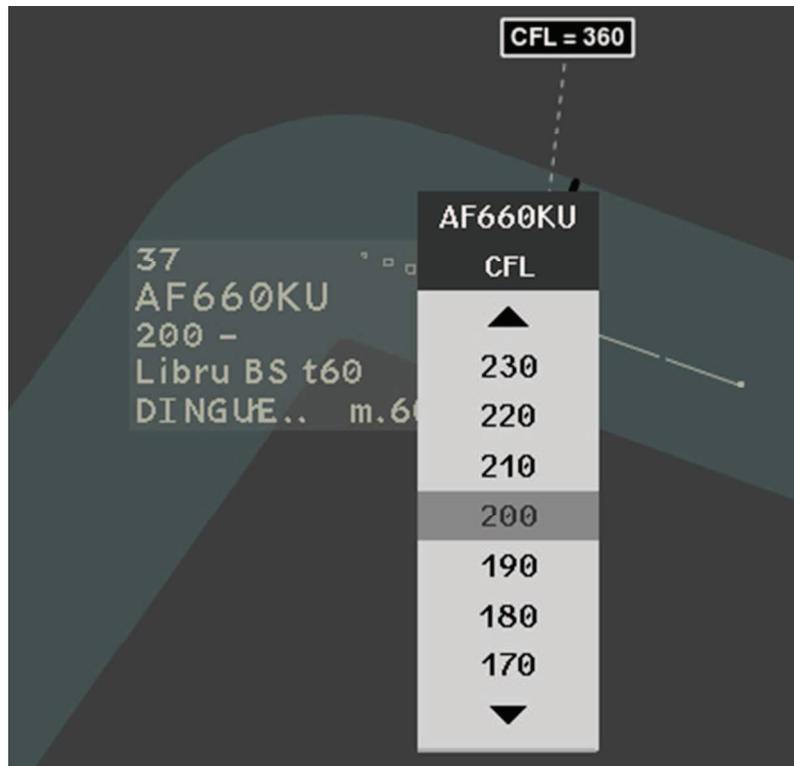


Figure 2. Screenshots of the drop menus for the control task (a) CFL orders
139x134mm (72 x 72 DPI)

View Only

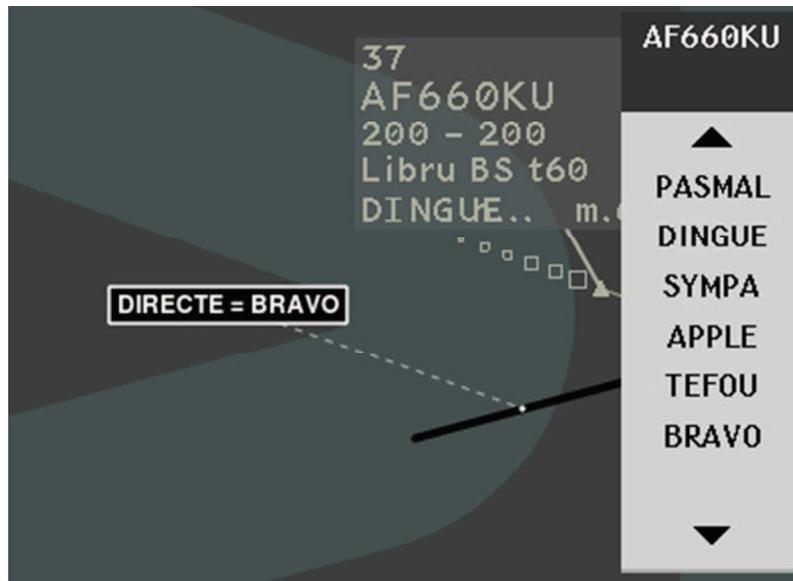


Figure 2. Screenshots of the drop menus for the control task (b) Direct orders
139x101mm (72 x 72 DPI)

Review Only



Figure 3. Notifications: (a) Color
51x32mm (100 x 99 DPI)

Peer Review Only



Figure 3. Notifications: (b) Color-Blink
102x56mm (96 x 96 DPI)

Peer Review Only

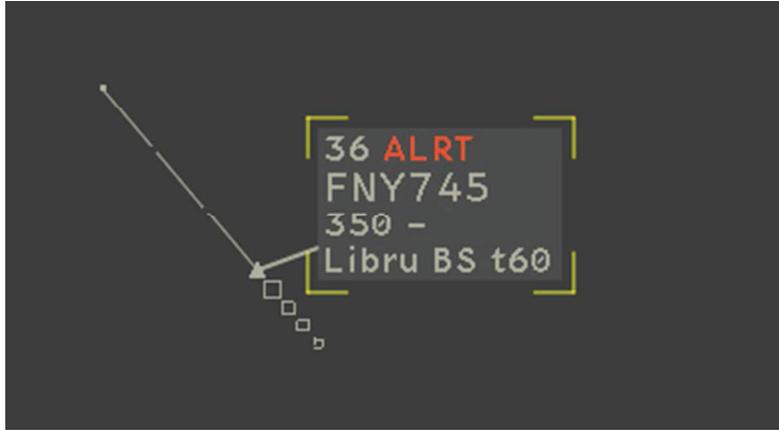


Figure 3. Notifications: (c) Box-Animation
102x56mm (96 x 96 DPI)

Peer Review Only

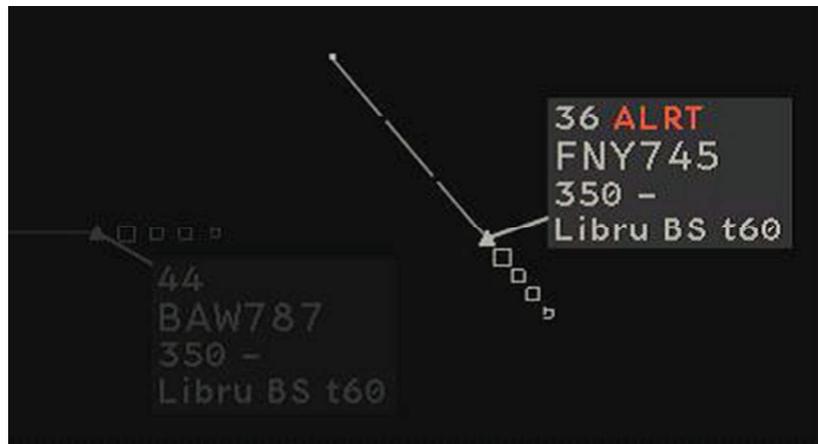


Figure 3. Notifications: (d) Shadow-mask
107x58mm (96 x 96 DPI)

er Review Only

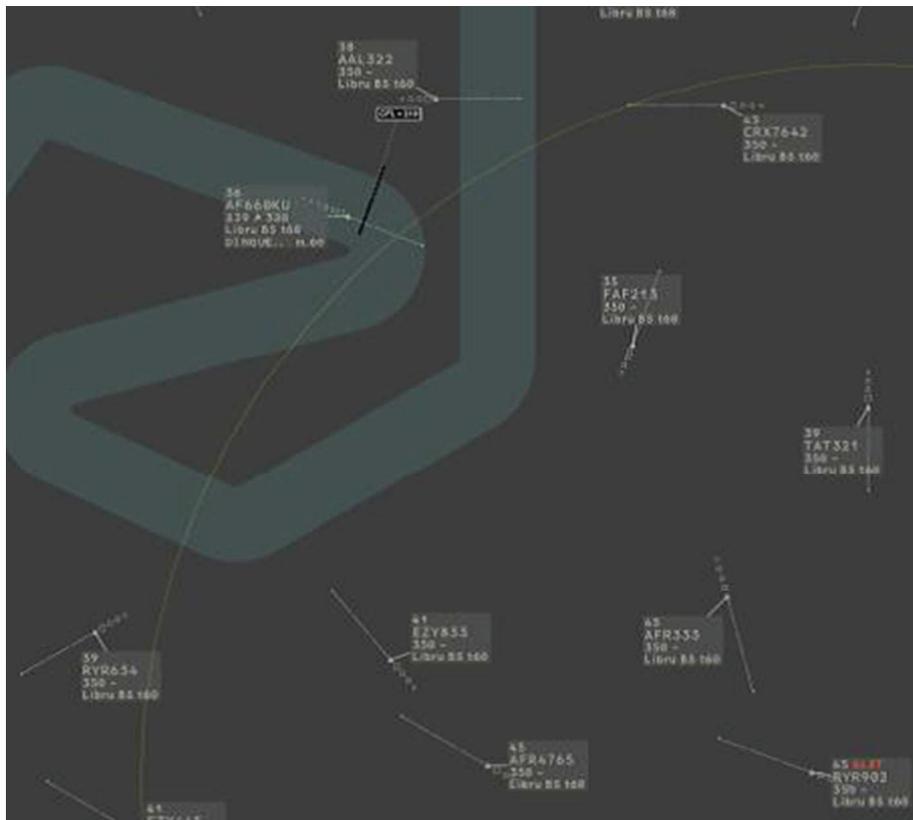


Figure 4. Halo notification
120x108mm (96 x 96 DPI)

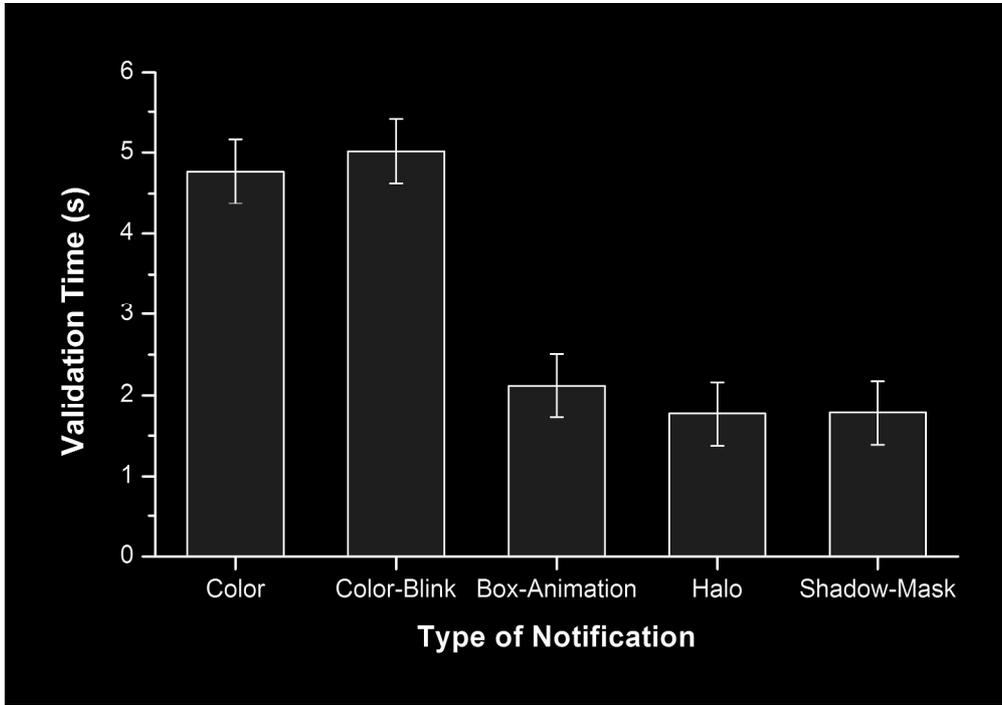


Figure 5. Validation time (in s) for each type of notification. Error bars represent 95% within-participant confidence intervals with Masson and Loftus's (2003) method.
235x165mm (300 x 300 DPI)

View Only

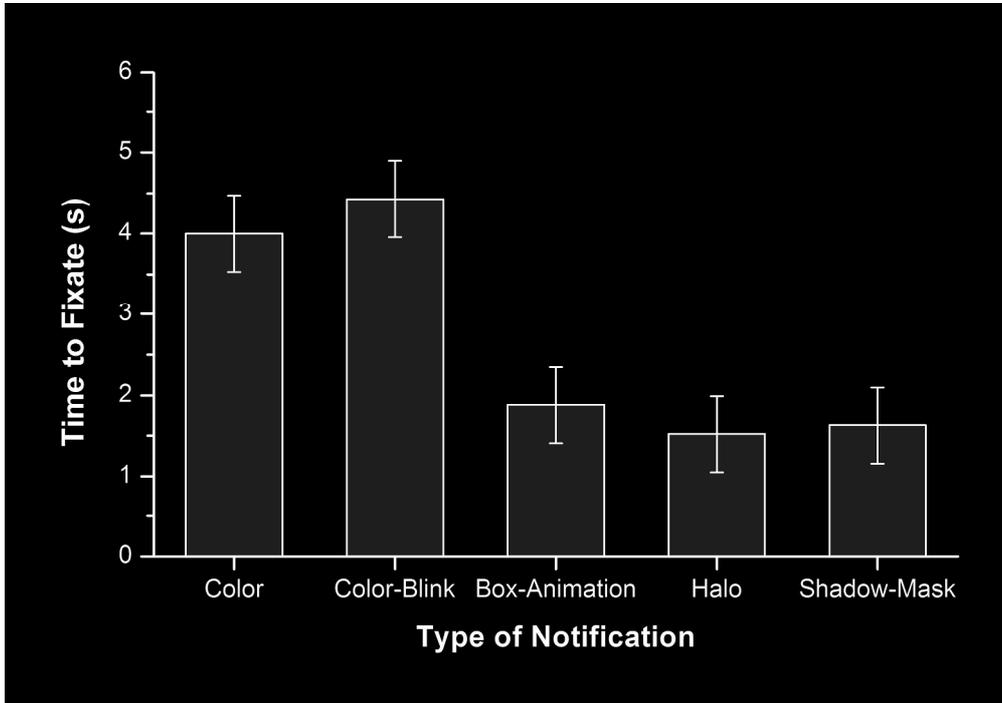


Figure 6. Time (in s) from notification onset until fixation for each type of notification. Error bars represent 95% within-participant confidence intervals with Masson and Loftus's (2003) method.
234x165mm (300 x 300 DPI)

View Only

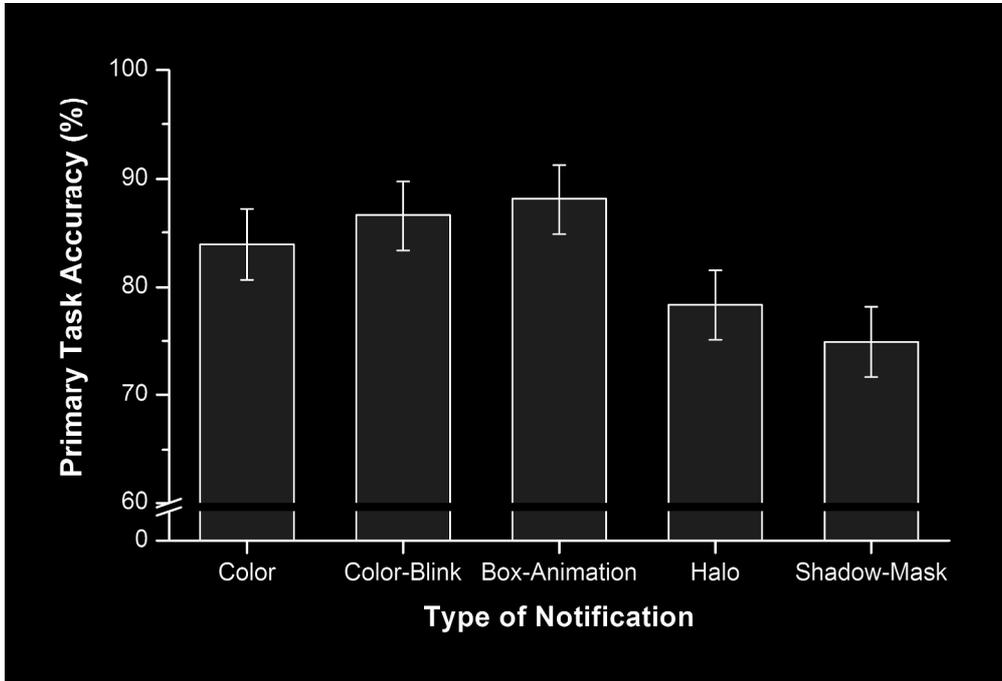


Figure 7. Accuracy level at the primary task (in %) for each type of notification. Error bars represent 95% within-participant confidence intervals with Masson and Loftus's (2003) method.
241x164mm (300 x 300 DPI)

View Only