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Display Compellingness: A literature review

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Contents

Introduction 1
Definition 1
Literature Review 2
Head-Up Displays (HUDs) 3
Frame of Reference: 3D perspective displays 6
Realism 7
Peripheral Displays 8
Mitigation of Cognitive Tunneling 9
Conclusion 9
References 11

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16. Abstract

Avionics, such as synthetic vision systems, head-up displays, and electronic flight bags, have been described as being "compelling" but such a description is not quantifiable, Compellingness is a property of the display, that attracts attention (a cognitive behavior), at the expense of attention allocated to other tasks and to other displays, for a long duration of time. Compellingness can be beneficial; e.g., when attention is drawn to information when that information is time-critical (e.g., compelling alerts) or when information is presented in such a way that it reduces the "cost" of accessing or integrating that information. However, compellingness may also have negative impacts, and such prolonged attention has been referred to attentional tunneling (to the physical world) or cognitive tunneling (to a single task relative to the array of tasks confronting the pilot). The purpose of this paper was to try to establish a link between the physical features of display compellingness and the manifestations of cognitive/attentional tunneling to identify features that lead to compellingness and gather metrics to define it.

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Introduction

The task of aeronautical decision making requires pilots to integrate information from a variety of sources ranging from installed avionics displays, portable devices, what they observe out-the-window, and what is communicated by air traffic control. These information sources all have different levels of accuracy, integrity, and reliability, so the pilot must be able to direct his/her attention (visual scan) in such a way that is reflective of the usefulness and reliability of the information source. As a very basic example, the task of aviating (maintaining stability in attitude relative to the horizon) is the pilots' highest priority task (compared to navigate and communicate), but in visual meteorological conditions (VMC), the relevance of the two areas of interest is equally divided between the true horizon and the artificial horizon. In instrument meteorological conditions (IMC), the out-the-window view is no longer relevant to aviating because the true horizon cannot be seen.

Computational models can predict how attention should be "optimally" allocated given the frequency with which changes occur in each area of interest and the usefulness and value of the display (Wickens, Goh, Helleburg, Horrey, & Talleur, 2003). In addition, the pilot's attention is also found to be driven or constrained by other factors:

- The effort of accessing information: greater effort to scan to more peripheral AOIs reduces the tendency to scan there.
- The effort or difficulty of extracting information from an AOI once scanned. Greater effort typically leads to a longer dwell time or gaze duration on the AOI.
- The compellingness of the display or AOI. Greater compellingness leads to more frequent scans and longer dwells.

It is this compellingness component that is the focus of the current paper.

Definition

Compellingness is a property of the **display** that attracts **attention** (a cognitive behavior), at the expense of attention allocated to other tasks and to other displays. Compellingness can be beneficial; e.g., when attention is drawn to information when that information is time-critical (e.g., compelling alerts) or when information is presented in such a way that it reduces the "cost" of accessing or integrating that information. However, compellingness may also have negative impacts, and such prolonged attention has been referred to **attentional tunneling** (to the physical world) or **cognitive tunneling** (to a single task relative to the array of tasks confronting the pilot). It is one expression of poor **cockpit task management** (Funk, 1991). Thus, compellingness of one display may lead to **task neglect**, and/or it may lead to decisions that are different from and at odds with decisions that should be based on other neglected sources of information (e.g., the decision to proceed with a landing, rather than go-around, given a neglect of visibility information; because of the compellingness of a flight guidance display).

The interest of this project is to establish the link between:

1. Physical features of display compellingness, including:
    - Realism
    - Motion
    - Color in a display
    - 3D immersive perspective
    - Head-up display (HUD) location

And

2. Manifestations of cognitive/attentional tunneling,
    - when visual attention to a display is longer than visual scanning models would dictate and this leads to a neglect of other information (Moray, 1986; Wickens, 2015)
    - When uninterrupted time on one task is sufficiently long that other important tasks become neglected (Wickens, Gutzwiller, & Santamaria, 2015)
    - When a decision is made that is clearly incorrect, and it can be attributed to focusing on an inappropriate cue or source of information.

The need to understand the appropriate amount of attention is of vital importance here. For example, there is nothing wrong with a compelling Primary Flight Display (PFD), given that it may keep the pilot's eyes fixated on this critical flight deck information for a long period of time particularly in IMC. A compelling alert will be necessary to redirect the pilot's eyes (and brain) to the source of abnormality in the cockpit. However, in the multi-tasking environment of the cockpit, it is necessary to prevent such focus or redirection of attention, from being longer than appropriate. Additionally, we distinguish between the concept of compellingness and pilot distraction. Although both situations represent a case in which a display receives an unwarranted amount of attention, compellingness describes when one's attention is drawn *to* an information source whereas distraction describes when one's attention is drawn *away from* an information source.

We reviewed the research literature to try to identify features that may lead to compellingness and gather the metrics used to measure compellingness.

Literature Review

We identified the following as desirable, and sometimes necessary, components of a study that demonstrated compellingness, to be included in this review.

1. An empirical study (containing experimental data)
2. A display that is said to be compelling (or "engaging") by the authors, or contained characteristics known by our team to create compellingness: movement, color, immersed frame of reference, 3D, dynamic ownship representation.
3. An alternative (control condition) display of the same information. That is, a display that does not contain that "compelling" element.
4. A task that was either (a) performed concurrently with another task and is supported by the compelling display, whose performance is measured in both conditions, OR (b) a task whose performance is found to be sub-optimal because of overreliance on the display, which is said to be compelling or where the data shows an "overabundance" of scanning to the compelling display, versus to other areas of interest.
5. In an aviation context.

Although we tried to find studies that included all five criteria, in some cases, one or more of these components was sacrificed if we believed that critical data were nevertheless embodied in the article. There are two areas that are not addressed in this review. The first is the important class of research on cockpit warnings (Wickens, Sebok, Walters, & McDermott, 2016), even though a specific feature of such warnings is that they are designed to be "compelling" and attract attention to a particular discrete event in time. This is because, in such displays, compellingness is a **desirable** attribute, whereas our current review addresses the problems or challenges of more continuous compelling displays. A second class of literature not reviewed here, describes a series of more basic studies demonstrating attentional narrowing of the visual field, caused by an increase of task workload of a central task, rather than the compelling nature of that task. See Wickens, Sebok, et al. (2016) for a review of this literature.

We start by addressing research related to **head-up displays (HUDs)** and the combination of information in the near domain (display) with that in the far domain (out-the-window view). The **frame of reference** with which HUD and other imagery is presented also has implications for compellingness, and that issue is discussed second. We then consider the effects of **display realism** and the **location of the display**, before concluding with some potential mitigations.

Head-Up Displays (HUDs)

A very early concern with the introduction of HUDs, based on a simulation study by Fisher, Haines, and Price (1980), and replicated by Weintraub, Hanes, and Randall (1984), is that the compelling nature of the HUD overlaying the out the window view (i.e., the far domain information), could distract pilots from noticing critical events in that far domain, such as a runway offset (relative to HUD navigational guidance), or a runway incursion. The underlying theoretical interpretation is that depth at which the information is presented – either the near domain (display) or the far domain (out-the-window) – provides an important cue for selective attention. As a result, pilots filter out information in the far domain when they are focusing their attention on the HUD display, even as such information lies within the primary field of view when eyes are focused on the HUD information.

While the fact that processing of one element (HUD information) may disrupt processing of a safety critical spatially adjacent element in the far domain is of some concern, it is not surprising that this occurs with HUDs given the well-known phenomenon of change blindness (Rensink, 2002; Stelzer & Wickens, 2006). The more important issue here is whether such detection failure, attributed to “HUD compellingness” is worse than the disruption caused by equivalent information presented elsewhere in the cockpit (i.e., head down). This issue is addressed in detail in papers by Prinzel and Risser (2004) and by Wickens, Ververs, and Fadden (2004). A quantitative answer to this question is provided by Fadden, Ververs, and Wickens (2001), who conducted a meta-analysis of 22 studies that had compared performance supported or disrupted by displays between the two locations, (head up and head down) and differentiated performance between continuous tracking (flight control) and discrete event detection and recognition (e.g., noticing a runway incursion). They found that over all tasks, there was a significant ($p<.01$) benefit to the HUD location, indicating that the HUD benefits of reduced visual scanning compared to the head down location, dominated any costs of overlaying clutter.

However, there **was** a small cost, to discrete event detection, which was observed exclusively during landing, but not during takeoff and cruise. When these costs were examined in detail, it was found that they were only statistically significant when the event was unexpected (such as would be the case with the unexpected runway incursion, originally studied by Hanes and his colleagues). This finding was consistent with that of Beringer and Ball (2004), conduced subsequent to the meta-analysis. They found that detection of airborne targets was significantly delayed by the HUD location of a highway-in-the-sky display (HITS) compared to the head down location of the HITS. More discussion of the compellingness property of the HITS itself is presented below. The findings of the meta-analysis also mirrored one subsequently observed by Yeh, Merlo, Wickens, and Brandenburg (2003) comparing performance using a head-mounted (see through) display versus a hand-held (head-down) display. Detection of unexpected events was slightly disrupted by the head-mounted display location.

In evaluating the *cost to unexpected event detection* created by the “compelling” HUD, it is important to consider the extent to which those events are in the far domain (like the runway incursion) or in the near domain, such as a HUD-displayed warning light, or appearance of a discrete guidance command. This issue was examined by Fadden, et al. (2001) (whose data are included in the meta-analysis reported above), and revealed that perception of display events (near domain) was supported by the HUD location. The perception of most far-domain events was supported by the HUD location as well; but replicating earlier findings, perception of **unexpected** far domain events was **not** supported by the HUD location.

We also note that HUD visual intensity or contrast can influence the relative "noticeability" of far domain events. Not surprisingly, an intense HUD image will diminish the visibility of far domain elements such as traffic, viewed through the HUD, as observed by both Ververs and Wickens (1998) and by Nichol (2015). However, it is probably not appropriate to label this as an example of psychological "compellingness", as it can be better described to reflect differences in perceptual visibility related to visual masking.

A final factor that could affect the compellingness of a HUD, is the nature of the flight path display information contained therein, specifically whether this is conformal (e.g., a "3d" perspective rendering) or non-conformal (e.g., a standard ILS guidance symbology). The 3D rendering of outside, far domain information has sometimes been associated with the concept of "scene linking" (Levy, Foyle, & McCann, 1998) or *conformal imagery*, in which elements on the HUD, both overlay and are designed to move in synchrony with their counterparts in the far domain as the aircraft rotates and translates. Such dynamic properties of the visual HUD information are designed to bring attention outward, hence integrate near and far domain information and, as a result, lead to better processing of all far-domain information (including unexpected discrete events).

In the studies reported above comparing head-up versus head-down display location, the compellingness of the imagery was measured via discrete event detection, with higher miss rates symptomatic of display compellingness. As we have described, the results of these studies indicate a benefit for the head-up presentation in reducing visual scanning and keeping eyes out, but also a cost in detecting unexpected events. This cost has been found to be mitigated by the use of conformal, scene-linked imagery. As reviewed by Wickens and Alexander (2009), such scene linking has generally been successful in supporting unexpected event detection. That is, HUD costs for far domain event detection appear to be mitigated when 3D scene linked displays are employed; but not eliminated altogether. This conclusion then leads to consideration of the extent to which 3D flight-path guidance and terrain displays themselves, independent of their location (HUD or head down) may produce a compellingness of the 3D guidance information at the expense of processing other information, an issue addressed directly by Wickens and Alexander (2009) and discussed in more detail below.

In conclusion, the compellingness of the HUD does not appear to be a major concern, and its advantages far outweigh its costs. But these costs, to detecting unexpected events in the far domain, should be acknowledged and probably addressed through training rather than design recommendations. However designs that include more conformal imagery (e.g., 3D perspective displays) appear to reduce these specific HUD costs. 3D displays can themselves be considered compelling independent of their location, and we now address this issue.

Frame of Reference: 3D perspective displays

Some context for this issue can be provided by considering three alternative *frames of reference* within which flight navigational information can be presented (Wickens, 2000; Wickens, Vincow, & Yeh, 2005; Wickens & Prevett, 1995). (1) A 2D or plan view display is the typical ILS display coupled with some form of vertical situation display. (2) A 3D exocentric or “god’s eye” display presents the airspace view as if from a camera above and behind the aircraft, looking forward. (3) A 3D egocentric display presents a “pilot’s eye” or “immersed” view of the world. It is this view that presents the forward looking “highway in the sky” (HITS), and it is also the frame of reference from which a **synthetic vision systems** rendering of the terrain and airspace ahead of the aircraft is presented (Prinzel & Wickens, 2009). Because this immersed view mimics that of the pilot’s forward line of sight, it is often argued to be “compelling,” in contrast to the other two frames of reference.

Ample evidence supports the finding that the 3D immersed frame of reference, in particular, when supported by the HITS, provides superior flight path tracking (i.e., reduced flight technical error) in both lateral and vertical deviations, as well as deviations from command airspeed. (Haskell & Wickens, 1993; Theunissen, Roefs, & Etherington, 2009). However, some evidence suggests that the immersed 3D frame may inhibit detection of unexpected events such as those discussed in the previous section on HUD compellingness. Olmos, Wickens, and Chudy (2000) for example concluded that the immersed 3D view inhibited the detection of traffic, which was presented on a separate traffic display. Fadden, Ververs, and Wickens, 2001 (experiment 1) compared a conventional ILS HUD with a HUD depicting the HITS. While they replicated the benefits of the HITS for flight-path tracking and they also observed HITS benefits for noticing discrete changes on the display, as well as significantly (11%) greater accuracy, but an increase in response time (1.3 seconds longer) for noticing traffic in the airspace ahead. However, examining detection of **unexpected** events, they observed that the HITS display imposed a marginally significant 4 sec delay in detecting a runway offset (misalignment between the runway and the guidance symbology) on final approach, thus suggesting some cognitive tunneling induced by the HUD HITS. But this cost was offset by a large, but non-significant advantage for the HITS in detecting a blocked turnoff on the runway after landing. The absence of significance was a result of the low N for this type of event. Thus these findings of 3D compellingness replicate those of HUD compellingness: generally an advantage for the “non-conventional” display (HUD, or 3D immersed), but a potential cost for detection of unexpected discrete events in the far domain.

The findings of Fadden et al. (2001) in the HUD location appear to be confirmed by a series of seven studies that contrasted 3D SVS displays with conventional flight instruments in both cases located head down. These studies, summarized by Wickens and Alexander (2009), were all conducted in a relatively high-fidelity flight training device, presenting a wide-screen rendering of the outside world, with an SVS display hosting a HITS. During routine flight, at all phases (take-off, cruise, arrival), occasional unexpected hazards were presented. Typically, the hazard would be a blimp or unmanned air vehicle in the outside world that was not presented on any of the head down navigational displays. As described above, the SVS-HITS suite typically supported better flight path tracking; but the unexpected hazards were **missed** at a 52% rate (averaged across all experiments), in contrast to the 28% miss rate of the far domain hazard when pilots flew with the conventional display, a significant cost to detection. One of these studies included in the meta analysis examined visual attention allocation via eye movements, and suggested that this OTW detection cost for the HITS was related to a greater proportion of time scanning this display, compared to the conventional ILS display (Thomas & Wickens, 2004).

We emphasize here that this compellingness cost of the HITS to unexpected OTW event detection, is borne only for events that are **not also rendered** on the head down display, and most traffic would be represented on a separate traffic display. It is also important to note that, while the SVS 3d perspective view of the terrain is typically coupled with the HITS, this coupling is not mandatory, and other evidence suggests that the SVS terrain view is advantageous in avoiding terrain hazards relative to not having a conformal terrain view (Prinzel & Risser, 2004).

Realism

There are several ways to convey realism: time resolution, display resolution, and motion are examples. Beringer and Ball (2004) investigated the possibility that more realistic, higher-resolution, weather displays could create a compellingness that induced greater trust in and reliance upon the displayed information than lower-resolution displays. Specifically, the goal of the research was to examine if using the full resolution of the available data was or was not wise given that the data could be as old as 12 minutes, and whether the pilots would use the display strategically, as recommended, or tactically. Their data in a flight simulation experiment indicated that pilots, using the higher-resolution display decided to fly longer into simulated IFR conditions, as if trusting that the higher-resolution would better enable them to negotiate around the bad weather.

Although not in an aviation context, Yeh and Wickens (2001) found that greater realism of simulated terrain, led participants to place greater trust and reliance on automation cues to dangerous events overlaying that terrain, even when such cues were not entirely reliable. Under such conditions, we might argue that the compellingness of greater realism led to problematic behavior (over-reliance upon automation).

Realism may also be conveyed through motion. One manifestation of this examined by Yeh et al. (2018) examined a moving ownship representation on a taxi map display used in low visibility conditions, to assess whether the compellingness of such motion could divert flightcrew attention away from the out-the-window (OTW) forward view. The researchers found that the captain (but not the first officer) spent substantially more time scanning the map display (and less OTW) when it contained a moving symbol than when it did not. However, this change in scan strategy was not considered to be distracting because it did not degrade taxiing performance, nor lead to any reduction in response to an unexpected failure of ownship position depiction. Rather, the fact that the Captain looked almost equally at the portable device as s/he did out-the-window when ownship was presented on the electronic chart may speak to the utility of ownship position representation, which may have made its presentation compelling. In other words, *compellingness* in this sense should not be interpreted as negative; rather, the presentation of ownship reduced the information access cost for determining position.

In a separate taxi study conducted in low visibility conditions, Wilson, Hooey, Foyle, and Williams, (2002) found that presenting command guidance information on a taxiway moving map display, produced a lower (rated) position awareness of the outside world, than a display that presented scene-linked positional information relative to the taxi-path. The command-guidance symbology, which displayed predicted deviation from the desired path in a non-conformal manner, may have induced cognitive tunneling, which manifested in increased deviations from the taxi path and a sense of increased workload.

Peripheral Displays

It is certainly the case that features of the interface design on a Personal Electronic Device (PED) or electronic flight bag have been found to produce distraction away from the primary flight display (e.g., Joslin, 2013; Chase & Hiltunen, 2014), and many of such incidences of distraction are reviewed elsewhere in this report. However, there is a distinction between such peripheral displays being a source of distraction – either because of the information they contain, or because of their interface design – and the features of such displays that may make them compelling, such as color, frame of reference, or moving aircraft symbol. Our review has revealed little objective evidence for or against such compellingness, so we also looked to see if there were any subjective reports that supported such conclusions. We conducted a cursory search of the Aviation Safety Reporting System (ASRS) database for reports that provided evidence of over-reliance on portable displays. We found many reports related to ownship position (in-flight or on the surface), but only a few of these reports were related to compellingness or over-reliance. For example:

> *Using new smart phone GPS navigation program on direct flight and didn't pay enough attention to the primary GPS and map…I won't let my attention be diverted again. My normal navigation was to use a panel mounted LORAN, the panel mount GPS and to cross check VOR's on the route of flight. CAVU day and just watching the panel mount and moving map on the phone program contributed to an error on navigate*. (ACN 942384)

> *I blindly followed the graphic display instead of confirming on the approach plate the correct direction to turn inbound.* (ACN 1028956)

> *We followed the map more than paying attention to signs* ... (ACN 1040638)

Mitigation of Cognitive Tunneling

Whether cognitive tunneling is caused by a compelling feature of a peripheral display or by some other feature of the task supported by a peripheral display, a small number of researchers have examined ways to "break through" the cognitive tunnel. Loveday and Wiggins (2014) have validated the benefits of salient icons on the peripheral display itself, to redirect attention back to the primary flight display, should the "intelligence" of the software driving such a display to infer that such tunneling has taken place (and the PFD neglected). In a slightly reversed twist on this issue, Causse et al. (2013) have addressed an issue when cognitive tunneling is on the PFD itself and leads pilots to ignore addressing a more peripheral warning alert. Here they find that a very temporary dimming of the PFD, can break through this tunnel, and facilitate the pilot's redirection of attention to the more peripherally located alerting symbol. It remains unclear whether the extent to which the research on this issue is so limited is due to aviation researchers concluding that the problem of compellingness is not a severe one, or that the solutions achieved by attention redirects are fairly difficult to implement.

Conclusion

In conclusion, there appears to be surprisingly little research on the concept of display compellingness. One source of challenge to research here may be the difficulty of imposing and obtaining reliable statistical measures of delayed responses to unexpected off-nominal events, such as the runway incursion. Such events, whose detection delay is a strong indicator of compellingness, must by definition be presented only once to render them truly surprising (Wickens, 2009; Wickens & McCarley, 2017).

To complement such findings and avail a richer data base, we propose the development of a subjective compellingness scale, analogous to the Cooper-Harper workload scale. To evaluate a display, a compellingness scale should only be used in a pilot-in-the-loop simulation, when the pilot is actively using the display to perform a typical flight task. Passive viewing of the display to gather this data would not be sufficient. Ideally, the scale should also be incorporated in comparison with a baseline display.

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