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THE EFFECT OF VISUAL LOCATION ON COGNITIVE TUNNELING WITH SUPERIMPOSED HUD SYMBOLOGY

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Cognitive tunneling occurs when the pilot's attention becomes locked on non-conformal, superimposed head-up display (HUD) symbology, while neglecting to scan the out-the-window scene, as a result of locating the HUD symbology near (in visual angle) the outside scene information (Foyle, McCann, Sanford & Schwirzke, 1993). Previous studies have shown that cognitive tunneling could be eliminated by placing the HUD symbology at least 8 deg from the out-the-window path being tracked. Limitations to previous research have included experimental designs that tested participants in multiple HUD information locations without fostering an efficient eyescan strategy for any one HUD location. Experiment 1 dedicates a participant to a single HUD location with blocked presentation. The results indicate that cognitive tunneling is not only eliminated by placing HUD symbology greater than 8 deg, but path tracking performance improves with symbology placed in an upper location on the HUD. Experiment 2 shows that the resulting performance decrement when information is overlaying the path (0 deg) may be associated with symbology compellingness, regardless of symbology relevance to the task.

INTRODUCTION

Superimposed symbology on aircraft HUDs was designed to allow pilots more time directly viewing the external world, while retaining awareness of aircraft status. Symbology detailing aircraft status information (i.e., altitude readout) is collimated at optical infinity on the HUD and aligned with the pilot s forward field-of-view (Foyle, McCann, Sanford, & Schwirzke, 1993). Fixed-location information is superimposed on the out-the-world view, such that digits on the HUD show differential motion with the terrain overlaid. Studies of simulated flight over a designated path have shown placement of a superimposed altitude display on the HUD can positively or negatively influence optimal path performance (Foyle, McCann, Sanford, & Schwirzke, 1993; Shelden, Foyle, & McCann, 1997). In strategic flight maneuvers, where both path navigation and altitude maintenance are required, optimal placement of displayed altitude information is imperative.

In dual-task desktop flight simulations, Brickner (1989) and Foyle, Sanford, and McCann (1991) found a performance tradeoff between path tracking performance (an out-the-window task) and altitude maintenance performance (a HUD task). This first portion of the tradeoff occurred when superimposed HUD altitude information (presented in the center of the screen) yielded better altitude maintenance, but with decreased out-the-window path performance. Whereas, without HUD digital altitude information, altitude maintenance was poor, but path-following ability was improved: thus, a performance tradeoff related to HUD location. Errors in flight performance with superimposed symbology suggest a decrement in path navigation may be associated with a cost in attentional shifting between the HUD symbology and the forward scene (Shelden, Foyle, & McCann, 1997).

The inability to successfully allocate attentional resources due to inherent characteristics of the HUD may foster cognitive tunneling. This phenomenon occurs when the pilot s attention becomes locked on one source of information, while neglecting to attend to other items in the environment. Pilots flying with a HUD may fixate on HUD symbology to the detriment of optimal situational awareness. When flying with a HUD, pilots become susceptible to cognitive tunneling thereby becoming vulnerable to the possible hazards of unexpected events in the environment (Wickens, Fadden, Merwin, & Ververs, 1998). The compellingness of some HUD symbology has been shown to capture attention at the expense of detecting unexpected events in the visual environment (Ververs & Wickens, 1998).

Foyle, McCann, Sanford, and Schwirzke (1993) reported failures to simultaneously process both sources of information (superimposed, altitude HUD symbology and out-the-window path), when information locations were less than 8 deg visual angle apart. When location of HUD symbology exceeded 8 deg from path information, this performance tradeoff was eliminated, and efficient processing of both HUD and path information was achieved. Foyle et al (1993) proposed that a mitigating effect of visual distance, necessitating saccadic eye movements, may break cognitive tunneling on the HUD symbology (see Weintraub & Ensing, 1992) when performing a dual task of path tracking and altitude maintenance.

Further extending the results of Sanford, Foyle, McCann, and Jordan (1993), Foyle, Dowell, and Hooey (2001) sought to eliminate possible confounds that could lead to other explanations for the presence of a performance tradeoff. Confounds of differential contrast, complexity, and motion between HUD and background were identified and addressed in an attempt to eliminate them. Previously unmatched luminance levels of sky and ground were perceptually matched utilizing the technique of heterochromatic flicker photometry method (see Cornsweet, 1970). HUD symbology was changed from white to bright green in order to portray more realistic flight instrumentation. Two levels of symbology-to-background luminance were established and defined by contrast ratios (symbology luminance divided by background luminance): 28.80 (High Contrast) and 7.48 (Low Contrast).

Superimposed HUD symbology was located at equal screen distances both above and below the horizon, in order to independently assess the effects of distance and effects of background varying in complexity and motion. HUD digital symbology was presented in four unique screen locations. The four HUD locations were measured in degrees of visual angle from the path information as follows: Center (0 deg, directly overlaying the path information); Mid-Upper (7.71 deg, intermediate distance upwards from the path information); Upper (15.43 deg, left corner of the screen, far from the path information); Lower (15.43 deg, left corner of the screen, far from the path information). Participants were tested in a single contrast level (between-subjects factor). All subjects were tested on the four HUD symbology locations plus a fifth HUD Absent condition serving as an experimental control (within-subjects factor).

Results from this study found no effect of Contrast for both Altitude and Path Root Mean Squared Error (RMSE) dependent measures. Replicating previous findings (Foyle, McCann, Sanford, & Schwirzke, 1993; Shelden, Foyle, & McCann, 1997), altitude maintenance performance without a HUD digital display (HUD Absent condition) was worse than when HUD altitude information was presented in any location (Figure 1). When HUD altitude information was displayed in the Center location, path tracking performance was worse than when presented in any other HUD locations or when the HUD was absent. Additionally, path tracking performance for Mid-Upper and Lower HUD locations was equal (not significantly different) to performance when no HUD was presented (HUD Absent).

Surprisingly, placement of HUD symbology in the Upper location yielded marginally better path tracking performance than all other HUD locations (including absent), with no associated performance tradeoff in the altitude maintenance task. Foyle, Dowell, and Hooey (2001) concluded that when HUD symbology is located greater than 7.71 degrees diagonally from the path information (Mid-Upper HUD location), the dual task performance tradeoff is eliminated. Visual distance was suggested as a necessary component to allow efficient processing of HUD and outside world information, thereby mitigating cognitive tunneling through requisite eye movements.

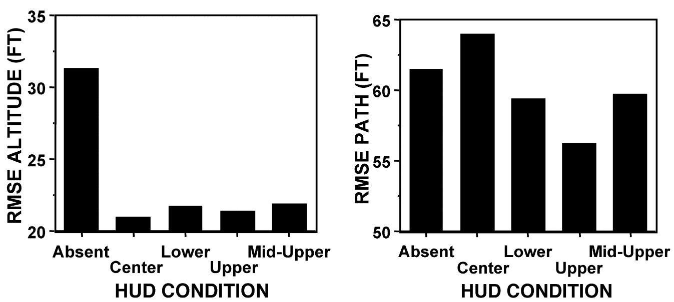

Figure 1. Mean performance results averaged over the two contrasts tested (*n* = 32): Effect of HUD condition on Altitude RMSE (left) and Path RMSE (right) from Foyle, Dowell, and Hooey (2001).

It is unclear whether the Upper HUD location actually improves path performance, over and above the Lower and Mid-Upper locations (both > 8 deg). Previous studies have not found significant path improvement (Foyle, McCann, Sanford, & Schwirzke, 1993; Shelden, Foyle, & McCann, 1997) when an Upper HUD location was presented. This marginal finding may have merely been an artifact of the experimental design. Results from previous research (Foyle, Sanford & McCann, 1991; Foyle, McCann, Sanford & Schwirzke, 1993; Foyle, Dowell, & Hooey, 2001) were reported from within-subjects design experiments in which subjects were tested across all HUD locations. The unblocked presentation of HUD symbology may have prevented participants from developing efficient visual scan patterns for any specific HUD location. Furthermore, use of a HUD absent control condition presented on only one fifth of the trials (Foyle, Dowell, & Hooey, 2001), could have affected participants effort level on this qualitatively different condition: maintaining a constant altitude (100 ft.) without an altitude display instead utilizing pictorial cues of the virtual environment. Given these concerns, an additional study was proposed to collect more robust data specifically using a between-subjects design.

EXPERIMENT 1

Purpose of the Study and Hypotheses

The purpose of this study was to investigate the effects of symbology location on flight performance in a dual task simulation, where participants might develop eyescan strategies by testing in a single HUD location with a HUD absent condition serving as an experimental control. It was expected that participants might improve strategies for maintaining altitude without a digital altitude readout if dedicated to this task for half of the experiment, and that this blocked HUD presentation would foster the development of eyescan patterns and performance strategies, yielding overall improved performance. Specifically, it was hypothesized that regardless of HUD location, subjects would perform better on the altitude maintenance task with an altitude display than without. Furthermore, it was hypothesized that participants presented with a Center HUD location (0 deg, directly superimposed) would show a decrement in the path tracking task, yielding an altitude/path performance tradeoff since the distances were less than 8 deg. Lastly, it was hypothesized that participants would both show superior performance on the path tracking task when presented with an Upper HUD location (15.43 deg) and incur no associated performance tradeoff on the altitude maintenance task, when compared with other HUD locations. In testing this hypothesis, it was predicted that an improved eye-scan strategy from blocked presentation and a single HUD location tested would offer more robust findings for overall improved performance in the Upper HUD location than previously reported (Foyle, Dowell, & Hooey, 2001). It was anticipated that performance advantages previously found would be amplified from the presentation of a HUD in a single location, thus differentiating effects of HUD symbology located above and below the horizon line.

METHOD

Participants

Forty-eight right-handed, male participants with normal or corrected-to-normal vision were tested in this experiment. All participants were 18 - 30 years old with normal ability to perceive color. Participants had no previous experience with HUDs in either simulated or actual flight.

Apparatus

Participants completed the simulation while seated in a dark room insulated for sound reduction. The flight simulation was viewed on a 19-in Silicon Graphics color monitor, located 65 cm from the participant's vantage point. Control of simulated flight was maintained through the operation of a spring-centered joystick located in the right arm of the participant's chair. Joystick sampling, data collection, and graphic presentation were updated at 12 Hz.

Simulation

The experimental simulation represented operation of a pseudorotorcraft kinematically flown through a virtual environment at dusk. The visual scene measured 32.18 deg horizontal (H) by 24.31 deg vertical (V). The virtual environment depicted a blue sky adjacent to a green ground, with a horizon line dividing the screen in equal halves. Terrain was overlaid with green gridlines that appropriately scaled with flight. Sky and ground luminance were matched such that the symbology/background contrast was perceptually equal (HUD luminance divided by background luminance = 28.80). Eight paths comprised of 38 pyramids marked the designated route. Superimposed HUD symbology, depicting relevant altitude information, was presented in one of three screen locations: Upper, Center, or Lower (Figure 2). Digits measuring .62 deg (V) and 1.06 deg (H) were displayed in bright green, graphically overlaid on the forward scene. An absent condition where no digits were presented served as an experimental control.

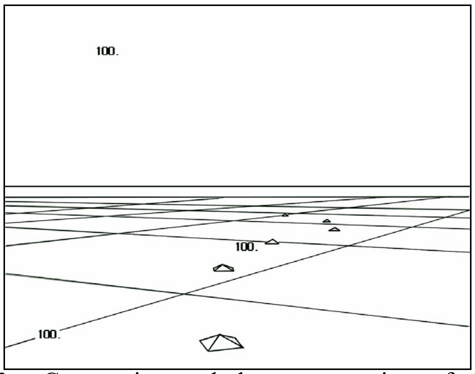

Figure 2. Composite scaled representation of the flight simulation. The three HUD locations are shown: Center (directly overlaying path, 0 deg); Lower (15.43 deg diagonal from Center); and, Upper (15.43 deg diagonal from Center).

Design and Procedure

A mixed design with repeated measures was conducted. The between variable was HUD location, consisting of three levels: Upper, Center, and Lower. The within variable of interest was HUD presence (On/Off). Experimental within variables were Block (1 - 7) and Trial (1 — 6). HUD location was blocked with counterbalanced presentation, such that 6 trials displayed HUD symbology and 6 did not, for a total of 12 trials per block. Each participant completed a total of 84 trials. The dependent measures were root mean square error (RMSE) altitude and RMSE heading. Errors in altitude performance were determined by deviations from the goal altitude (100 ft.). Errors in heading performance were determined by deviations from a hypothetical line segment connecting pyramids, denoting the optimal path.

Each participant completed one 2.5 hour experimental session. Instructions included information about error scoring and feedback at the end of each trial. Path and altitude error scores were displayed after each trial. Participants were instructed to focus equally on both path tracking and altitude maintenance. Participants utilized pictorial cues of the scaled virtual environment to maintain target altitude (100 ft.) in the HUD Absent condition.

RESULTS

A 3 x 2 x 3 x 6 mixed design ANOVA (HUD location x HUD presence x Block x Trial), with associated planned comparisons, were conducted separately on Altitude and Path RMSE data. Data analyzed was a subset of data collected, determined by identifying asymptotic performance with a technique used previously (Foyle, Dowell, & Hooey, 2001). As a result of this technique, Blocks 5 - 7 [3 replication blocks of 2 levels of HUD presence (Present/Absent) containing 6 trials each for a total of 12 trials per block] were deemed to be asymptotic, and included in the analysis. Only data from these 36 trials are reported.

Altitude Performance

As expected, results for altitude performance showed a main effect of HUD presence, such that target altitude was better maintained with an altitude digital display than without, $F\ (1, 45) = 114.30, p < .001$. No main effect of HUD Location was found. No interactions between factors were found (Figure 3). In summary, altitude performance was better with an altitude display than without. No other effects were significant.

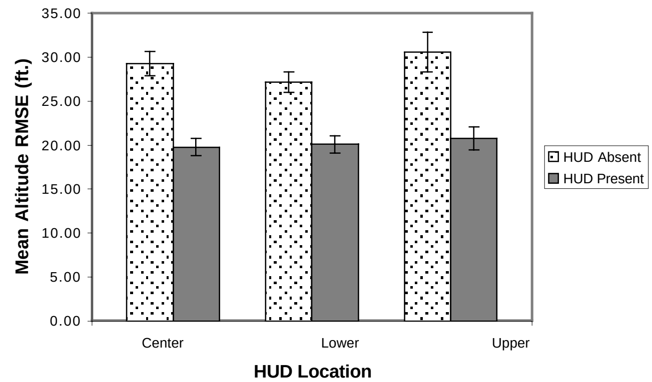

Figure 3. Mean altitude RMSE (with +/- 1 standard error) scores for HUD locations tested in both Absent and Present conditions (*n* = 16 per HUD Location group).

Path Performance

Analyses on Path RMSE scores yielded no main effects of HUD Presence or HUD Location. As expected, results on path performance included a significant interaction between factors: HUD Location x HUD Presence, $F\ (2, 45) = 3.14, p = .05$ (Figure 4). In order to determine the source of this interaction, planned pairwise comparisons within HUD locations between the HUD absent and HUD present conditions revealed a reversal in performance ability when examining the Center and Upper HUD locations. Previous research findings (Foyle, McCann, Sanford, & Schwirzke, 1993; Foyle, Dowell, & Hooey, 2001) supported directional hypotheses in performance comparisons for the Center and Upper HUD locations, which made one-tailed t-tests of significance appropriate.

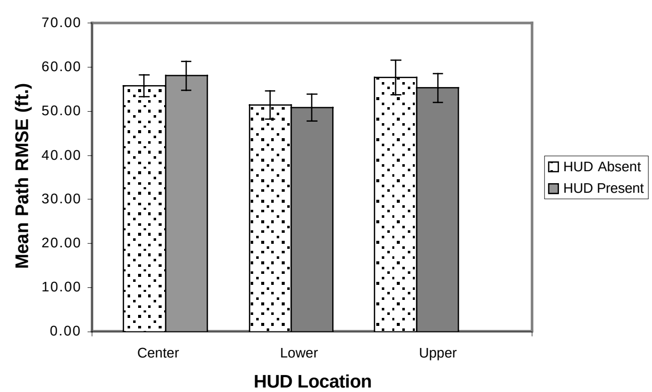

Figure 4. Mean path RMSE (with +/- 1 standard error) for HUD locations tested in both Absent and Present conditions (*n* = 16 per HUD Location group).

In the first comparison, path tracking performance with a Center HUD altitude display yielded better performance with marginal significance when the HUD was absent (*M* = 55.79) than present (*M* = 58.04), *t* (one-tail)(15) = 1.56, *p* = .07. A reversal of these results was found in comparing path tracking performance when an Upper HUD display was absent (*M* = 57.65) versus present (*M* = 55.24). Path tracking performance with an Upper HUD display location yielded lower error scores with marginal significance when the altitude display was present than absent, *t* (one-tail)(15) = 1.59, *p* = .065. No difference in error scores for the Lower HUD location was recorded, regardless of presence (*M* = 50.86) or absence (*M* = 51.45), *t*(15) = .62, *p* = .54.

In summary, path performance was negatively affected when the altitude display was presented in the center of the visual scene (overlaying the path), whereas performance was positively affected when the display was presented in the upper portion of the visual scene (15.71 deg from the path). The presence or absence of the HUD in the lower portion of the visual scene had no effect. The anticipated interaction of HUD location and HUD presence supported the experimental hypothesis and previous studies demonstrating a performance tradeoff when symbology is presented near the flight path.

DISCUSSION

The purpose of this study was to investigate the effects of HUD symbology location on a path tracking and altitude maintenance task. Negligible differences in altitude performance with a display were not surprising in consideration of previous findings for increased altitude performance when an altitude gauge is present (Sanford, Foyle, McCann, & Jordan, 1993). Analyses of Path RMSE data showed a degradation of performance when symbology is located in the center field of view, which replicated previous findings (Foyle, Dowell, & Hooey, 2001). Furthermore, the data revealed enhanced altitude maintenance when symbology was placed in the Upper location, without an associated cost in path tracking. In general terms, only the positioning of an altitude HUD in the upper portion of the visual scene allowed for <u>both</u> better altitude maintenance and better path tracking performance.

As hypothesized, this experiment was able to better assess differences between Upper and Lower HUD locations by testing subjects in a single HUD location. Comparisons between Lower and Upper HUD locations suggest that differential path performance might be attributed to the differences in background scene information/symbology. Clutter from overlaid contours of symbology placed on a more detailed ground as compared with a solid, detail free sky might provide explanation for performance variance on detailed terrain.

EXPERIMENT 2

The goal of Experiment 2 was to eliminate possible explanations other than visual distance between Center screen location symbology and path information as the source for the performance decrement in the path tracking task. It is possible that centrally located (i.e., 0 deg), symbology obscured relevant path information, resulting in hindered processing of path information. Another explanation might include the nature and saliency of a dynamic gauge placed in the center field of view. As altitude adjustments were initiated, the altitude gauge updated with corresponding information, yielding a dynamic symbology presented in HUD-like bright green. The compellingness of this presentation might have accounted for performance decrements with symbology located in the center field of view, regardless of the information presented. In order to test these alternate explanations, it was necessary to collect similar dual-task data on dynamic symbology presented 0 deg from path information, yielding information irrelevant to the task. In this way, the effects of compelling symbology could be separated from symbology that is necessarily attended for relevant information. An additional static symbology condition allows for a similar assessment with less compelling symbology (non-flashing).

METHOD

Sixteen right-handed, male participants with normal or corrected-to-normal vision were tested in this experiment. The abilities, ages, and skills of the participants met the requirements outlined in Experiment 1. The apparatus, data collection measures, experimental simulation and virtual world from Experiment 1 were used. Superimposed, dynamic HUD symbology, depicting irrelevant numerical information (random numbers between 50 — 149, inclusive), was presented in the Center screen location (0 deg). Digits were updated at 3 Hz. Alternately, superimposed, static symbology was presented at the nominal readout (100). An absent condition in which no digits were presented served as an experimental control. Participants followed the experimental procedure outlined in Experiment 1.

Design

A within-subjects design with repeated measures was conducted. The within variables were HUD motion (consisting of three levels: Static, Dynamic, or Absent/control) and Block (1 - 29). HUD motion was randomized within each block, such that a block consisted of 3 trials. Each participant completed a total of 87 trials. The logic utilized in Experiment 1 for a blocked presentation of altitude information did not apply: No HUD visual scanning was required, since all HUD information was irrelevant. The dependent measures were root mean square error (RMSE) altitude and RMSE path as defined in Experiment 1.

RESULTS

A 3 x 15 within-subjects ANOVA (HUD motion x Block) was conducted separately on Altitude and Path RMSE data. Data analyzed and reported consisted of 45 asymptotic (as previously defined) trials. Planned comparisons on effects of HUD motion were conducted on altitude and path performance independently.

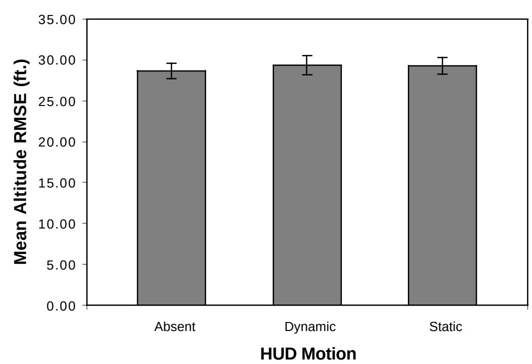

Figure 5. Mean altitude RMSE (+/- 1 standard error shown) for levels of HUD Motion (*n* = 16).

As expected, results for altitude performance showed no main effect of HUD motion (Figure 5), such that target altitude was not maintained differently whether irrelevant symbology was static (*M* = 29.29), dynamic (*M* = 29.35), or absent (*M* = 28.65), *F* (2, 30) < 1. No main effect of Block was found. No interactions between factors were found. In summary, altitude performance was not different across levels of HUD motion or different when absent.

Results for path performance showed no main effect of HUD motion, such that path tracking ability was not differentially affected as a result of static (*M* = 54.31), dynamic (*M* = 54.01) or absent symbology (*M* = 52.29), *F* (2, 30) = 2.54, *p = .10*. However, it should be noted that there is a trend for path performance with irrelevant dynamic and static symbology to have higher error scores when compared with the Absent (control) condition. No main effect of Block, or any interactions between factors were found (Figure 6). In summary, dynamic and static symbology yielded marginally higher error scores, when compared with no symbology.

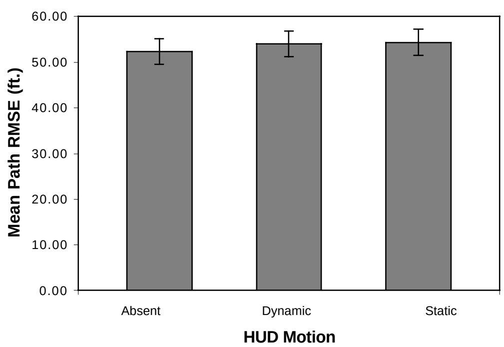

Figure 6. Mean path RMSE (+/- 1 standard error shown) for levels of HUD Motion (*n* = 16).

DISCUSSION

Experiment 2 addressed alternate explanations for path tracking performance decrements recorded when symbology was presented overlaying path information (0 deg). Findings revealed the possibility that symbology salience as a result of high contrast might hinder efficient processing of HUD information and world information. Although statistical significance was not found between levels of HUD Motion, the elevated error scores when symbology was present may imply an effect of Center location symbology, regardless of relevance to the task. In general terms, performance decrements recorded for the Center location symbology have replicated and possibly extended to presentation of irrelevant symbology. Although differences in path tracking ability across symbology presentations did not yield significance, trends toward hindered path tracking with symbology present should be noted. Similarly elevated path error data in both Dynamic and Static symbology conditions may suggest that compellingness of the symbology contributes to path tracking performance decrements when symbology is located in the center field of view.

CONCLUSIONS

Experiment 1 has important implications for the placement of HUD information within cockpit environments. Using a more robust experimental design, we confirmed previous findings showing that HUD information located less than 8 deg from the out-the-window point of interest can induce cognitive tunneling and impair performance on the task over which the HUD is superimposed. Similarly, this study showed that cognitive tunneling can be eliminated when the HUD information is presented greater than 8 deg from the out-the-window point of interest. Additionally, it was shown that HUD symbology placed in the upper portion of the visual scene (greater than 8 deg from the central focus), led to improved simultaneous processing of the HUD symbology and the forward view. It is hypothesized that this difference is rooted in the reduced clutter and background motion found when the HUD overlaid the sky, as opposed to the ground.

Lastly, Experiment 2 revealed a marginal impact to efficient processing of HUD and world information, when presented with irrelevant HUD information. These findings suggest that regardless of relevance, HUD information located less than 8 deg from world information may induce cognitive tunneling. Implications suggest that high contrast symbology contributing to symbology compellingness, may affect efficient processing, regardless of symbology relevance. Further examination of symbology salience in a high contrast presentation is warranted.

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