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Spatial Awareness Biases

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Abstract

Pilot performance models used for representing task demands with new display technology, such as Synthetic Vision Systems, should benefit from a module associated with spatial awareness. Such a module represents how the pilot understands his/her position and trajectory in the 4D space (X, Y, Z and time), with regard to the desired flight path and waypoints, and with regard to terrain, traffic and weather hazards.

This paper reviews and integrates the biases that have been documented through research in how the pilot's representation is influenced by features of the display of visual-spatial information. These biases can then be incorporated into such a model.

1. <u>Overview</u>

In previous research, we have described a model of attention and situation awareness that addresses most directly what Endsley (1995) has labeled level 1 SA, perceiving, attending, and "noticing" events in the airspace environment (Wickens & McCarley, 2001). However, in addition, the pilot/controller in a 4D world must at all times accurately understand where things **are** (level 2 situation awareness; Endsley, 1995) and where things **will be** with relation to each other (level 3 situation awareness). An accurate understanding is necessary, but not sufficient for an optimal action to be selected, since action selection (e.g., the choice of what maneuver to fly, or whether to land or go-around), is based not only upon situation awareness, but also upon internalized costs and values associated with different actions and their expected outcomes. Our focus in this paper is primarily upon the biases that may infect spatial situation awareness.

We begin by establishing a "gold standard" in which the pilot/controller (we shall, for convenience refer to this person as "the operator") has perceptual access to all relevant spatial information, and uses it to infer a perfectly accurate description of the relevant airspace. We will often characterize this description as a vector, which, optimally, is identical to the real world vector. Our reason for emphasizing the vector representation is twofold. First, the 3D orientation of the vector can represent: (a) a terrain surface (b) the vertical/horizontal aspect angle of ownship relative to a hazard (e.g., traffic, weather, terrain) or for the air traffic controller, the angle of two hazards relative to each other, (c) the vertical/horizontal aspect angle of ownship relative to a goal (e.g., a flight path or waypoint). Second, the length of the vector (a) corresponds to the distance from ownship to the above objects; (b) can represent speed, and, inversely time, when some sort of 3D projection (level 3 SA) is involved.

The operators' spatial information processing task can generically be represented as a form of multi-cue information integration (Brunswik, 1952). Thus there are typically several sources (cues) of dynamic information available – displayed – which must be attended (level 1 SA), and often integrated to compute certain **derived quantities**, such as the 3D orientation of a vector, or the time-to-contact, a quantity referred to as "tau" (Lee, 1976). Over the operators' past experience, these cues may have been correlated, with each other, or with the derived quantity. For example speed is typically correlated (negatively) with tau, since other things (distance) being equal, faster moving objects will contact in a shorter time.

In this general context, we propose that accurate spatial information integration may be thwarted by one of four mechanisms:

1. Increasing salience of certain cues may direct attention to their processing, at the expense of other cues that may be equally or more relevant and reliable for the spatial estimation task at hand (i.e., there is a higher correlation between the less attended cue and the derived quantity). For example Wallsten and Barton (1982) observed the biasing influence of salience on non-spatial information integration. Olmos, Wickens, and Chudy (2000) observed that salience differences across spatial aviation displays influenced event detection, and Horrey and Wickens (2001) found that salience differences influenced spatial threat integration in a 2D military combat simulation.

2. Differences in the effort required to interpret multiple cues may act to inhibit the contributions of those cues requiring greater effort to interpret. For example, Stone Yates, and Parker (1997) found that differences in effort necessary to process graphic versus digital risk information influenced risk perception. Based upon a comparative analysis of other studies, Alexander and Wickens (2002) have inferred that differences in the effort required to perceive vertical flight path information, between digital (higher effort) and analog (lower effort) representations, influenced pilots' choice as to whether to maneuver vertically in an air traffic conflict situation.

   It should be noted that effort and salience are not necessarily two sides of the same coin (e.g., more effort = less salience). The two constructs do behave in this way when a comparison is made across levels of display eccentricity from the normal line of sight (greater eccentricity leads to less salience and greater effort is required to access that information). However when the relevant variable is, for example digital versus analog information, then effort and salience are decoupled. A digital signal of altitude change can be more salient than an analog signal, but still require more effort to process if that altitude is to serve as the input to an altitude tracking task.

3. Decreased resolution of the perception of the magnitude of a cue may reduce its impact on the estimation of a derived quantity.

4. The larger effort required to **integrate** multiple cues in order to estimate the derived quantity may inhibit accurate estimation, and can be decoupled from the effort required to process the component quantities as in (2) above. As in (2) however, if the effort of integration is difficult, this mental computation may not be carried out at all, but be replaced by the processing of one of the single component cues (or by a simpler form of computation; e.g., addition replaces multiplication). Such a replacement may be said to be a "heuristic" to the extent that the single cue, or the simplified computation will usually be correlated, across perceptual experience, with the derived quantity. As discussed above, the positive correlation of distance with tau (whose estimation requires integrating distance with speed) is such an example. That is, differences in distance may be used as a heuristic to estimate differences in tau.

A factor that may mitigate the biasing influence of any of these mechanisms is metacognition (Reder, 1996); that is, the extent to which the operator is aware of these biases, as they influence his or her own spatial understanding. If the operator is aware, then performance and decision making may be modified in a way that we describe below. For example, being unsure of the location of a hazard, because of low resolution, the operator may as a consequence choose to behave on the "safe side", a form of adjustment that we describe as the "optimum conservative correction". For example a pilot who knows that she has a degraded estimation of the distance from a hazard may choose to fly farther from the hazard than a pilot who has accurate knowledge. Data suggest that such a conservative bias is adopted when judgments of time-to-contact are made both by non-specialized subjects (Schiff & Oldak, 1990) and by air traffic controllers (Boudes & Cellier, 2000).

In the following sections we catalogue the various spatial estimation biases in the following 2x3 framework:

VECTOR VARIABLE

		Distance	Time	Orientation
Dimensionality	2D			
	3D			

Following discussion of biases within these six cells, we introduce additional biases imposed by the geometric field of view, and by information integration, and then conclude by discussing the implications of these biases for choice.

2. 2D Distance

Maps vary in their scale. To properly estimate true distance one must view the separation between two points on a map (e.g., in centimeters or pixels) and divide it by the scale factor of the map (e.g., 1:1000 or, in this case, divide by 0.001). This division is assumed to require some cognitive effort whether it is done explicitly or implicitly, and it may be simplified by the effort-reducing heuristic: "longer map distance → longer true distance". Such a heuristic works accurately so long as all maps have a constant scale. But it could create biases when the operator is working, simultaneously or sequentially with maps of different scales (e.g., when zooming in and out of an electronic map; or when viewing the same map in large and small renderings). (In 3D "maps" or spatial displays, the feature of map scale is often approximated by the geometric field of view, or the gain of a display). To the extent that such a heuristic is employed, it would lead to the overestimation of distance on large scale maps (large scale is when the fraction: X cm/1 KM is large). The biases created by scale size can be assessed explicitly, if people are asked to estimate distances, or implicitly in one of two forms which we describe below as **urgency** (Boeckman & Wickens, 2001) and **resolution**. We also describe a related 2D distance bias called the "filled distance effect".

2.1. Urgency. To the extent that an operator overestimates a distance (e.g., a true distance -- the gold standard -- of one true KM "seems" like 2 KM), then two consequences will follow: (a) the separation from a **hazard** will be perceived to be greater than it really is, and therefore in less urgent need to be corrected. Safety may be compromised. (b) The separation from a **goal** (e.g., a desired flight path or waypoint) will be inferred to be greater than it really is, and therefore more urgently in need of correction in a closed loop tracking sense. As a consequence more aggressive control may be imposed and reduced tracking error may result. However, possible overcontrol and instability could also be a consequence, in that more urgent control is represented by a higher open loop gain the source of instability for systems with lags (Wickens, 1986). The finding of reduced error from larger map scale is supported by the observation of Abbott and Moen (1981) that a larger scale CDTI lead to pilots' reduced tracking error in a "miles in trail" target following task. This effect is further illustrated by Kim, Ellis, Tyler, Hannaford, and Stark (1987) and Kim, Tendick, and Stark (1993) in that performance (normalized RMS error on a tracking task and mean completion time on a target acquisition task, respectively) degraded with an increased FOV due to the smaller displayed object picture. This effect does not appear to be consistently observed however, in part because humans tend to be relatively proficient in adjusting their own gain to changes in map (display) gain (Wickens, 1986). In a 3D flight path tracking task Doherty and Wickens (2000) for example found only a small predicted display scale effect on vertical tracking, but one that was in the opposite direction to that predicted by an urgency mechanism for lateral tracking, as the gain of the 3D display was varied.

2.2. Resolution. When longer distances are represented by smaller screen size (small scale map), we saw above that this can lead to underestimation of those distances. However the decrease in screen size may also lead the operator to become consciously aware of their higher thresholds (poorer **resolution**) required to judge **differences** in distance, and therefore to consciously adopt the optimum conservative correction. ("I know that I cannot see a reduction in separation from a hazard because of low resolution, so I'll compensate by increasing separation"). We have not, however, found empirical data to support this effect.

2.3. The filled distance effect. Thorndyke (1980) reports that subjects amplify estimates of distance across maps that contain more items (e.g., a cluttered vs. uncluttered map). Wickens (1992) documents other examples of this.

3. **3D Distance**

When a 3D volume of space is projected onto a 2D viewing surface (Figure 1), this projection may have a variety of biasing effects which we describe as follows:

3.1. Between-map scale differences in Geometric field of view (GFOV). As we noted above, an increase in the geometric field of view of a 3D image map, placing a greater volume of spatial data (visual angle) within the same size display space, is equivalent to decreasing the map scale, and would be predicted to have corresponding effects on tracking performance. Barfield, Rosenberg, and Furness (1995) found evidence in support of this effect in that RMS error for flight path tracking was lowest (best) using a 30° GFOV compared to both 60° and 90° GFOVs. Contrary to this, however, Stark, Comstock, Prinzel, Burdette, and Scerbo (2001) reported an interaction such that horizontal flight path error was lower on the final segment of an approach with a 60° GFOV than with a 30° GFOV. The reason for this difference is not apparent.

3.1 Within-map differences in distance. If a perspective, rather than parallel projection is employed, then the lengths of vectors that are more distant along the line of sight, will be represented by fewer pixels on the display than those that are closer, hence leading to a possible underestimation of vector length (and separation) for more distant vectors following the logic offered in Section 2.This is represented in Figure 1, by comparing the vector length separating points A and B closer to the viewer, with that separating points C and D further away, yet both pairs are the same true distance apart. Note how much shorter is the displayed vector CD than that of AB. To avoid this bias, the operator may have to perform a sort of "mental stretching", by mentally integrating map (pixel) distance with relative distance in depth between the two vectors.

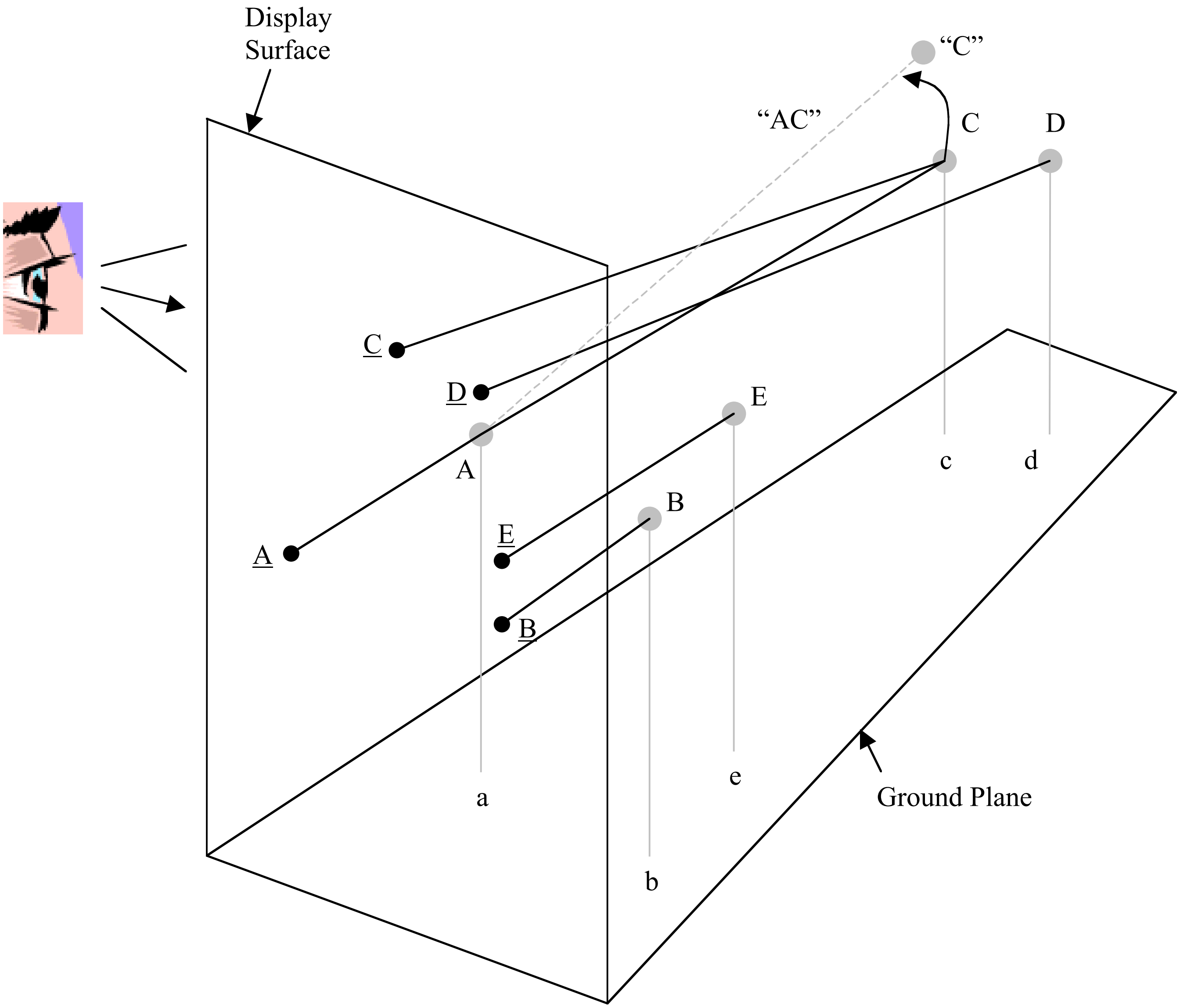

Figure 1. The figure depicts five points (A, B, C, D, and E) located in a 3D volume of space as designated by the large gray circles. The lower case points (a-e) show where these points are over the ground. The underlined points (A-E) with the small black dots show where these points would appear as projected on a 3D display viewed by the eye to the left. The display uses a perspective (rather than parallel) projection. For illustrative purposes, two of the gray points in true space are connected explicitly by a vector AC. The perceived orientation of this vector is represented as "AC" (the grey dashed line), and the mental rotation of the vector is indicated by the curved arrow.

3.2. Within map differences in orientation. To the extent that a vector is projected parallel to the line of sight into the display (and therefore orthogonal to the display plane), it will be represented by fewer pixels (compare vector AB with BE as projected on the display surface of Figure 1, two distances of equal length in the 3D space). In order to estimate true distance of such vectors as BE, an operator may need to “mentally rotate” the vector parallel to the viewing surface, an operation that Boeckman and Wickens (2001) describe as attaining “resolution through rotation”. As such rotation is cognitively demanding (Wickens, 1999, 2003; Aretz & Wickens, 1992), it may not be carried out, but rather replaced by the heuristic that “pixel distance = true distance”. As a consequence, distances along the line of sight may be underestimated. An example of how such underestimation appears to translate to reduced urgency in closed loop control was provided by Wickens, Liang, Prevett, and Olmos (1996) who found that aircraft lateral control error in a 3D display was greater (implicating less control urgency) when the lateral axis was oriented along the line of sight into the display, than when it was oriented parallel to the display plane (i.e., the aircraft was viewed from behind). Supporting findings were provided in a more abstract tracking task by Boeckman and Wickens (2001), who observed a continuous increase in tracking error, as the viewing angle was altered from orthogonal to the axis of control (low error) toward orientation parallel to the axis of control.

4. Time Biases

In dynamic systems, distance estimations and biases, as discussed above, have direct consequences for time, as mediated by system velocity (v). While there are several important biases related to time estimation itself, we will not cover these here, considering only those that are more directly related to the distance traveled during an interval of time. Our particular focus will be on time-to-contact, or **tau**, a derived quantity proportional to D/v or distance (from a moving body to a contact point) divided by velocity.

4.1. 2D tau. It is not surprising that data suggest that the estimation of tau, as vehicle icons are moving across a 2D display surface, is not entirely accurate. Such an estimation is what an air traffic controller must carry out, in judging which of two converging aircraft, traveling at different speeds, will cross a point in space first (or if, in fact, they will cross that point at the same time, creating a conflict or loss of separation if they are also at the same altitude). Because the mental division (D/v) required to estimate tau is complex, a heuristic may sometimes be used to approximate its value from its components. Of the two components, D and v, we argue that D is either more salient, or requires less effort to estimate than is v. Our basis for making this argument is grounded in several observations. (a) relative errors (Weber fractions) in estimating speed are greater than those in estimating distance (Debruyn & Orban, 1988; Mataef, Dimitrov, Genova, Likova, Stefanova, & Hohnsbein, 2000). (b) When operators track systems with varying control order dynamics, those of higher (second or above) order require the operator to act as a differentiator, responding on the basis of error velocity (McRuer, 1980; Wickens, 1986), and as a consequence are found to be more difficult to control as inferred from a variety of convergent measures (see Wickens, 1986). (c) Optimal control theory models of tracking performance achieve greater precision when the “error term” added to the operators’ estimation of rate-of-change, is adjusted to be greater than that added to the estimation of position (Baron, Kleinman, & Levison, 1970; McRuer, 1980). In other words, the best fitting model of tracking performance assumes that error velocity is estimated with less precision than is error magnitude.

As a consequence of the greater demands of processing v, than processing D, when both are variables relevant to a closure problem, we would predict that tau is more heavily influenced by distance than by speed, and indeed this seems to be the case (Law, Pelegrino, Mitchell, Fischer, McDonald, & Hunt, 1993): tau is underestimated (sooner contact, more danger) for closer slower objects, relative to faster more distant objects, providing evidence for the overweighting of distance relative to speed. That is, the easier to perceive quantity is weighted more than the difficult to perceive quality, when the two are integrated. One may ask whether biases in distance perception induced by differences in map scale (Section 2) might also influence tau. Accordingly, tau should be underestimated on smaller scale maps.

4.2. 3D tau. In 3D viewing, Tau is typically captured by the expansion or "looming" of objects as they approach the viewer (Kaiser & Mowafy, 1993; Lee, 1976). Thus size and expansion are often correlated cues. Because expansion is again a velocity (tau is inversely related to the rate of expansion), whereas size is estimated directly as a distance (e.g., the visual angle diameter of the expanding object), a plausible heuristic would be for the perceiver to approximate tau by size. As a consequence, tau should be underestimated (earlier contact, greater danger) for larger, farther objects, relative to smaller closer objects, a bias documented by DeLucia and Warren (1994). The extent to which this distance perception bias is preserved when 3D tau judgments are made with objects that are not on a collision course (Kaiser & Mowafy, 1993), remains unclear.

4.3. Global optic flow. Just as biases in time (tau) appear to be influenced by differences in the effort required to process both velocity (more effort) and distance, so it appears that estimates of speed may also show analogous biases (Larish & Flach, 1990). Global optic flow, (velocity/altitude), provides an intuitive estimate of speed. A general finding is that when perceiving egomotion on 3D displays, operators' estimates of true speed are biased or inappropriately affected by altitude, such that they do not adequately account for increased altitude in their intuitive formula (Owen & Warren, 1987). The lower global optic flow which results from viewing at higher altitudes is thereby judged to correspond to slower velocities. Such a bias would appear to result from the difficulty in perceiving distance (altitude). In our assessment of tau biases in 4.2, distance was actually inferred to be perceived more easily than speed. However, the important differences here is that in estimating GOF, altitude is not represented linearly in a 2D display, but instead, the distance above the ground must be estimated via some form of inference from depth cues, a cognitively demanding process. Hence the heuristic for estimating speed would be simply estimate the speed of movement of elements across the visual field.

5. Vector Orientation

5.1. 2D orientation. When estimating orientation on a 2D map, people appear to show some bias towards "canonical orientation" described as "rectilinear normalization". This bias is one to reconstruct directions as more associated with the 4 cardinal axes of space (e.g., north, south, east, west) and to reconstruct angles as closer to 90^{o} than is the case in reality (Wickens, 1992).

5.2. 3D orientation. A fairly consistent enduring bias in 3D displays is that of mentally "rotating" vectors more orthogonal to the line of sight (and parallel to the display plane) than is their true orientation. This bias is illustrated in Figure 1, in which the true vector AC is perceived to be rotated to a more vertical orientation, "AC", than is true. That is, the true orientation of AC is horizontal. But the observer perceives it to slope uphill. This rotation bias was elegantly demonstrated and modeled by McGreevy and Ellis (1986), who asked subjects to estimate azimuths between ownship and traffic aircraft in a 3D cockpit display of traffic information (CDTI). Perrone (1982, Perrone & Wenderoth, 1993) has described a related effect of "slant underestimation" whereby a surface viewed in depth is perceived as rotated toward the viewing plane; steeper than it is in reality (i.e., the slant **away** from the viewer is underestimated). The bias could be more accurately labeled "slope overestimation". One way of interpreting this orientation effect is that accurate perception of the true orientation of the vector (or plane) in depth requires cognitive integration of all existing depth cues. One very salient depth cue, and that which is most easily processed is height-in-the-plane. To the extent that height in the image plane is used to approximate the perception of slant (or vector orientation), since steeper slants lead to greater separation between the endpoints of the vector, then using this cue as a heuristic to estimate slant, will produce the observed bias.

In reviewing the literature on depth perception, Wickens, Todd, and Seidler (1989) have pointed out that the amount of perceptual rotation is related to the collective strength of the depth cues. As more depth cues are incorporated into an image, the rotation of a vector in depth toward its true orientation becomes less effortful, more natural and veridical. With fewer cues available rotation is more demanding, less easily carried out. The distance cue of height in the plane dominates, and the slope overestimation increases. (Clearly in the extreme, when all depth cues are abolished, the vector is seen in "2D" and height in the plane is the only cue remaining. Hence the slope is seen at 90 degrees, i.e., vertical.)

Alexander and Wickens (2002) have used this bias to explain the tendency of pilots to descend below a traffic aircraft, ahead and at the same altitude as ownship, when viewed on a 3D CDTI, shown in the top panel of Figure 2 (e.g., the depiction in Figure 1 if A was ownship and C was a traffic aircraft). Under these circumstances, the horizontal vector connecting the traffic and ownship is perceived as rotated upward (slanted) such that traffic ahead is more likely to be perceived above ownship, and hence a descent under, rather than an ascent over, the traffic aircraft is perceived to be the most efficient conflict avoidance maneuver. Such a tendency is not found when the same traffic conflict pattern is encountered with a 2D coplanar display.

(a)

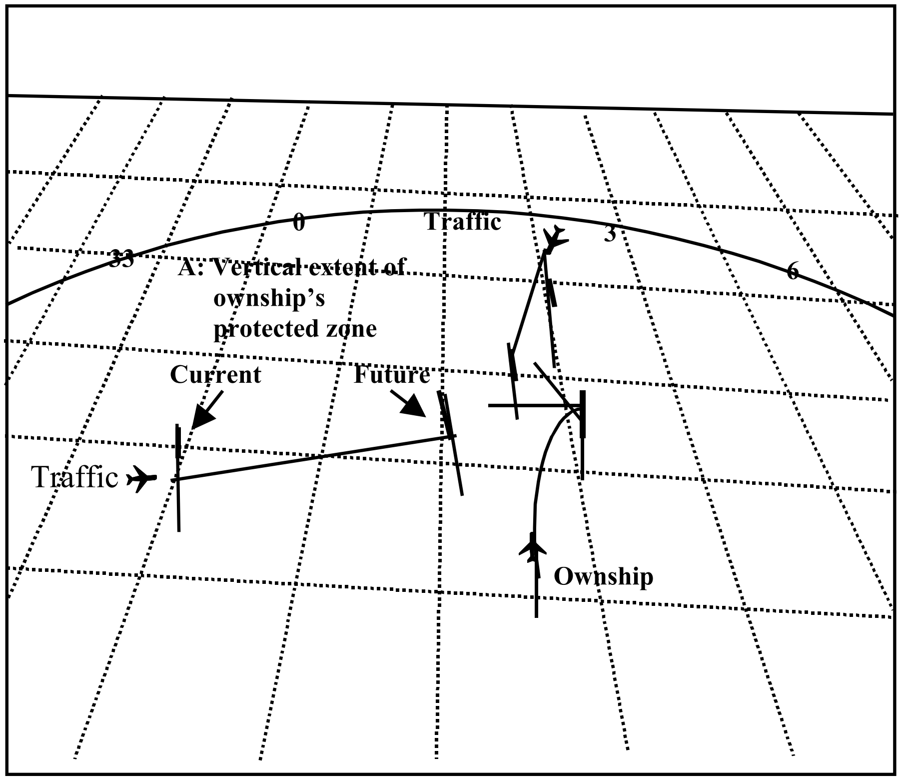

Figure 2 Three-dimensional CDTI, employed by Alexander and Wickens (2002).

5.3. 3D orientation and time. One issue that appears to have been little researched is the relation between tau biases as discussed in 4.1 and 3D orientation. For example, consider two aircraft flying toward a 3D intersection point as viewed on a 3D display; one flying more parallel and one more orthogonal to the image plane (the situation in Figure 1, would be if an aircraft located at A, and a second aircraft located at E, were both converging on an intersection point at B). Assuming that the two aircraft are on a collision course, the vector length between the aircraft and the collision point will be longer (more pixels) for the aircraft flying parallel to the image plane (AB). Will this longer perceived distance (to the collision point) translate into a longer tau (i.e., the viewer will judge this aircraft A to pass the collision point B later than in reality, judging that a collision will not take place?). This research question does not appear to have been examined.

6. The Virtual Space Effect

The virtual space effect, documented by McGreevy and Ellis (1986) is a bias produced whenever a 3D display is viewed that fails to preserve a unity relation between display width and geometric field of view, such that the azimuth (or elevation) angle of objects on the display do not correspond to their true azimuth and elevation, relative to the viewer's eyes.

These relations are shown in Figure 3. The station point (SP) is that location of a virtual camera that would depict objects (X and Y) in equivalent locations, whether they were projected on the display or in the real world. That is, when the observer's eyes are at the station point, the displayed objects would overlay their counterparts in the world. Thus, when the viewing distance to the display corresponds to the station point, as in panel (a), the viewer sees objects in their real location. (b) presents a magnified, narrow geometric field of view display with the same viewing distance as (a), objects X and Y are now perceived to be further apart (at a and b) than they really are. In (c), the minified display, with a large geometric field of view, objects are seen as closer together than their true separation. Note that with both (b) and (c), if the viewpoint were positioned at the station point (the black dot), objects would be perceived in their correction true orientation (azimuth and elevation).

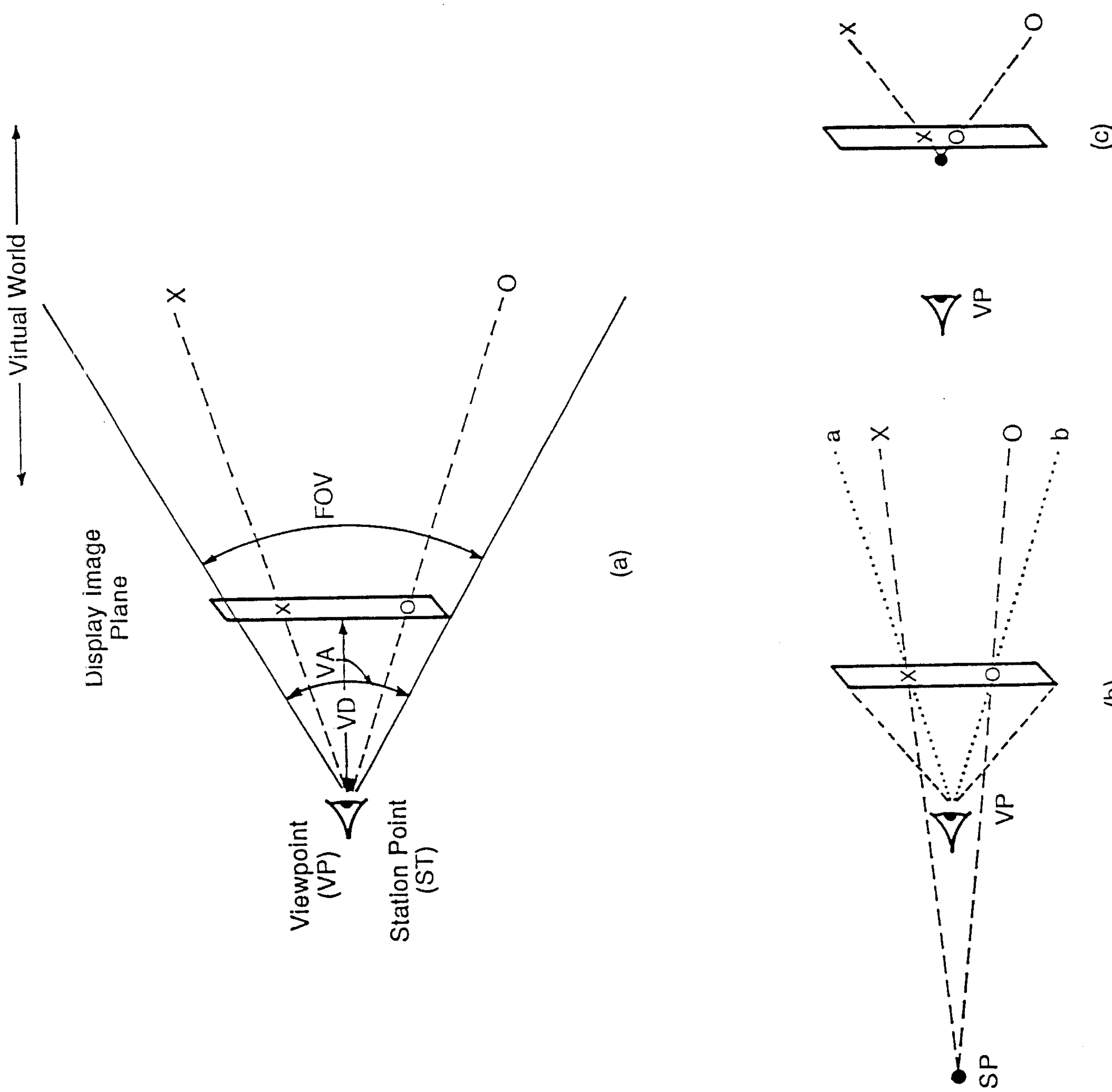

Figure 3. Illustrates the difference between a unity FOV (a), where the station point and view point coincide, a narrow (telephoto) FOV (b) and a wide FOV (c). In both (b) and (c), the station point of the display is shown by the black dot.

We may suppose that when such a non-unity gain is imposed, viewers must perform a "mental stretching" (on a wide angle display with a large GFOV as in (c)) or "mental compression" (small GFOV as in (b)) operation to understand elements in their true azimuth and elevation relative to the viewer, not unlike the map scale operations described in Section 2. Again, similar to these operations, to the extent that the viewer applies the heuristic "true location = pixel location" (or "true angle from display center = pixel distance from center"), then we anticipate the pattern of the distortions in understanding where things are. Elements will be perceived to be closer to forward viewing for the minified display (wide GFOV in (c)); and further away or more separated in the magnified display (b). Distortions of position estimation were observed by Wickens and Prevett (1995), when pilots flew with a wide GFOV 3D display. The finding that performance degrades with an increased GFOV observed by Kim et al. (1987, 1993) is also consistent with the distortions in position estimation due to the virtual space effect. That is, a given error will be perceived as smaller in the wide GFOV, and will therefore be less likely to be corrected.

7. Mental Effort of Integration

The previous discussion has focused on the perception of vectors of spatial information. As we have noted, sometimes multiple sources of that information must be integrated, and we propose that such integration will be made more difficult by more complex computations. That is certainly true with respect to mental arithmetic. For example, we can speculate that addition is easier than subtraction which is easier than multiplication which is easier than division. Such an ordering in difficulty is supported by research in simple mental arithmetic (Hall, 1947; Fuson, 1984; LeFevre & Morris, 1999). Many of these arithmetic operations are realized in the "spatial arithmetic" underlying the different transformations that we have discussed above. For example estimating tau from speed and distance involves division. Estimating a total distance of a set of flight legs involves addition; estimating distance remaining to a target involves subtraction; estimating the distance to be traveled from a speed and a time involves multiplication.

The relevance of these differences in spatial mental arithmetic effort to our current thinking is that the inherent ease or difficulty of these operations can: (a) influence the extent that heuristics are substituted for the arithmetic operation, in order to estimate the derived quantity (b) influence the extent that the estimation can benefit from display features that reduce the computational load of the integration. Examples of display features that ease computational integration, captured by the proximity compatibility principle (Wickens & Carswell, 1995) include: display overlay (Kroft & Wickens, 2001) assisting in judging differences, or 3D display integration (Haskell & Wickens, 1993), or emergent features, which can create a derived quantity directly from its components. As an example of the latter, Wickens and Andre (1990) created an object display whose features directly captured the complex computational relation between airspeed, pitch and bank, in graphically computing the margin of safety above stall speed. One might create a display that depicts tau as a direct spatial quantity (i.e., a "linear velocity count down graph"), rather than relying upon it to be estimated through intuitive mental division. Such creative graphics lie within the general domain of ecological interface design (Vicente & Rasmussen, 1992).

8. From Estimation to Choice

The previous pages have documented biases in estimation of vector characteristics. In aviation, most estimations are not ends in themselves, but rather, they are means to support some form of choice of action: which way to maneuver to avoid a conflict (Alexander & Wickens, 2002; Wickens, Helleberg, & Xu, 2001), which flight path to select around weather (Muthard & Wickens, 2001; Layton, Smith, & McCoy, 1994), whether an approach to landing is too high, and requires flying a missed approach (Leiden, Keller, & French, 2002), or even, in a simple analysis, whether a flight path error, in position, trajectory or speed (and tau) is large enough to warrant a corrective control action. In the context of our current discussion on estimation biases, it is important to realize that such choices themselves also depend upon the integration of information. The assessed spatial quantities discussed above represent one ingredient of these choices, but so also do quantities of:

- probability of an outcome, given that the chosen action taken in the given assessed state
- value (positive or negative) of the outcome-state combination
- expected value or risk of the choice (product of probability X value)
- cost (effort or financial) of executing each choice option

It should come as no surprise that this integration itself is imperfectly carried out, and can be approximated by many of the sorts of heuristics described above. For example value appears to weigh more heavily in choices than does probability; and in studies of safety behavior, effort cost ("cost of compliance") often weighs more heavily than expected value (e.g., in this case the expected cost of not behaving safely). Both of these biases can be used, in part, to account for the choice to engage in risky behavior (Wickens & Hollands, 2000). We do not in this paper intend to document more about the nature of these biases, except to note two points: (a) the ultimate implication of errors in spatial estimation for pilot/controller performance must account for how these errors are filtered through the choice process to generate performance. (b) There are indeed graphic ways of representing quantities of probability, value, expected value and cost, that can simplify the integration process, much as they can do the same for spatial integration, as discussed in Section 7.

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References

Abbott, T. S. & Moen, G. C. (1981). Utilization of traffic situation display for self-spacing task (Technical Paper 1885, Technical Report 81-B-4). Hampton, VA: NASA Langley Research Center, AVRADCOM Research and Technology Laboratories.

Alexander, A., & Wickens, C. D. (2002). Does traffic load modulate the effects of traffic display formats on performance (Technical Report 02-9/NASA-02-7). Savoy, IL: University of Illinois, Aviation Research Laboratory.

Aretz, A. J., & Wickens, C. D. (1992). The mental rotation of map displays. Human Performance, 5, 303-328.

Barfield, W., Rosenberg, C., & Furness, T. A. I. (1995). Situation awareness as a function of frame of reference, computer-graphics eyepoint elevation, and geometric field of view. International Journal of Aviation Psychology, 5(3), 233-256.

Baron, S., Kleinman, D., & Levison, W. (1970). An optimal control model of human response. Automatica, 5, 337-369.

Boeckman, K.J. & Wickens, C.D. (2001). The resolution and performance effects of three-dimensional display rotation on local guidance and spatial awareness measures (Technical Report ARL-01-4/NASA-01-3). Savoy, IL: University of Illinois, Aviation Research Laboratory.

Boudes, N., & Cellier, J. (2000). Accuracy of estimations made by air traffic controllers. International Journal of Aviation Psychology, 10(2), 207-225.

Brunswik, E. (1952). The conceptual framework of psychology. International Encyclopedia of Unified Science, 1(10), 1-102.

Debruyn, B. & Orban, G. (1988). Human velocity and direction discrimination measured with random dot patterns. Vision Research, 28, 1323-1335.

DeLucia, P. R., & Warren, R. (1994). Pictorial and motion-based depth information during active control of self-motion: Size-arrival effects on collision avoidance. Journal of Experimental Psychology: Human Perception and Performance, 20, 783-798.

Doherty, S., & Wickens, C. D. (2000). An analysis of the immersed perspective flight path display benefit: Benefit of preview, prediction, and frame of reference (Technical Report ARL-00-5/NASA-00-1). Savoy, IL: University of Illinois, Aviation Res. Lab.

Endsley, M. R. (1995). Toward a theory of situation awareness in dynamic systems. Human Factors, 37(1), 85-104.

Fuson, K. (1984). More complexities in subtraction. Journal for Research in Mathematics Education, 15(3), 214-225.

Hall, J. V. (1947). Solving verbal arithmetic problems without pencil and paper. Elementary School Journal, 48, 212-217.

Haskell, I.D., & Wickens, C.D. (1993). Two- and three-dimensional displays for aviation: A theoretical and empirical comparison. International Journal of Aviation Psychology, 3(2), 87-109.

Horrey, W. J., & Wickens, C. D. (2001). Supporting battlefield situation assessment through attention guidance and diagnostic aiding: A cost-benefit and depth of processing analysis (Technical Report ARL-01-16/FED-LAB-01-1). Savoy, IL: University of Illinois, Aviation Research Lab.

Kaiser, M. K., & Mowafy, L. (1993). Optical specification of time-to-passage: Observers' sensitivity to global tau. Journal of Experimental Psychology: Human Perception and Performance, 19(5), 1028-1040.

Kim, W. S., Ellis, S. R., Tyler, M. E., Hannaford, B., & Stark, L. W. (1987). Quantitative evaluation of perspective and stereoscopic displays in three-axis manual tracking tasks. IEEE Trans. on System, Man, and Cybernetics, SMC-17, 61-72.

Kim, Tendick, & Stark, (1993).

Kroft, P. D., & Wickens, C. D. (2001). Integrating aviation databases: Effects of scanning, clutter, resolution, and interactivity. Proceedings of the 11th International Symposium on Aviation Psychology. Columbus, OH: The Ohio State University.

Larish, J. F., & Flach, J. M. (1990). Sources of optical information useful for perception of speed of rectilinear self-motion. Journal of Experimental Psychology: Human Perception and Performance, 16, 295-302.

Law, D. J, Pelegrino, J. W., Mitchell, S. R., Fischer, S. C., McDonald, T. P., & Hunt, E. B. (1993). Perceptual and cognitive factors governing performance in comparative arrival-time judgments. Journal of Experimental Psychology: Human Perception and Performance, 19(6), 1183-1199.

Layton, C., Smith, P. J., & McCoy, C. E. (1994). Design of a cooperative problem-solving system for en-route flight planning: An empirical evaluation. Human Factors, 36(1), 94-119.

Lee, D. N. (1976). A theory of visual control of braking based on information about time-to-collision. Perception, 5, 437-459.

LeFevre, J.-A. & Morris, J. (1999). More on the relation between division and multiplication in simple arithmetic: Evidence for mediation of division solutions via multiplication. Memory & Cognition, 27(5), 803-812.

Leiden, K., Keller, J., & French, J. (2002). Information to support the human performance modeling of a B757 flight crew during approach and landing. NASA Ames Research Center, Moffett Field, CA.

Mateeff, S., Dimitrov, G., Genova, B., Likova, L., Stefanova, M., & Hohnsbein, J. (2000). The discrimination of abrupt changes in speed and direction of visual motion. Vision Research, 40, 409-415.

McGreevy, M. W., & Ellis, S. R. (1986). The effect of perspective geometry on judged direction in spatial information instruments. Human Factors, 28, 439-456.

McRuer, D. T. (1980). Human dynamics in man-machine systems. Automatica, 16, 237-253.

Muthard, E., & Wickens, C.D. (2001). Change detection and the confirmation bias in aviation route planning (Technical Report ARL-01-18/NASA-01-9). Savoy, IL: University of Illinois, Aviation Research Lab.

Olmos, O., Wickens, C. D., & Chudy, A. (2000). Tactical displays for combat awareness: An examination of dimensionality and frame of reference concepts and the application of cognitive engineering. The International Journal of Aviation Psychology, 10(3), 247-271.

Owen, D. H., & Warren, R. (1987). Perception and control of self-motion: Implications for visual simulation of vehicular locomotion. In L. S. Mark, J. S. Warm, & R. L. Huston (Eds.), Ergonomics and human factors: Recent research (pp. 40-70). New York: Springer-Verlag.

Perrone J. A. (1982). Visual slant underestimation: A general model. Perception, 11, 641-654.

Perrone, J.A. & Wenderoth, P. (1993). Visual slant underestimation. In S. R. Ellis, M. Kaiser, & A. J. Grunwald (Eds.), Pictorial communication in virtual and real environments. London: Taylor & Francis.

Reder, L. M. (1996). Implicit memory and metacognition. Mahwah, NJ: Lawrence Erlbaum.

Schiff, W., & Oldak, R. (1990). Accuracy of judging time-to-arrival: Effects of modality, trajectory and sex. Journal of Experimental Psychology: Human Perception and Performance, 16, 303-316.

Stark, J. M., Comstock, J. R., Jr., Prinzel, L. J., Burdette, D. W., & Scerbo, M. W. (2001). A preliminary examination of situation awareness and pilot performance in a synthetic vision environment. Proceedings of the 45th Annual Meeting of the Human Factors & Ergonomics Society (pp. 40-43). Santa Monica, CA: Human Factors and Ergonomics Society.

Stone, E. R., Yates, J. F., & Parker, A. M. (1997). Effects of numerical and graphical displays on professed risk-taking behavior. Journal of Experimental Psychology: Applied, 3(4), 243-256.

Thorndyke, P. W. (1980, December). Performance models for spatial and locational cognition (Technical Report R-2676-ONR). Washington, DC: Rand Corporation.

Vicente, K., & Rasmussen, J. (1992). Ecological interface design: Theoretical foundations. IEEE Transactions on Systems, Man, and Cybernetics, 22(4), 589-606.

Wallsten, T. S., & Barton, C. (1982). Processing probabilistic multidimensional information for decisions. Journal of Experimental Psychology: Learning, Memory, and Cognition, 8, 361-384.

Wickens, C. D. (1986). The effects of control dynamics on performance. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), Handbook of perception and performance (Vol. II, pp. 39-1/39-60). New York: Wiley & Sons.

Wickens, C. D. (1992). Engineering psychology and human performance (2nd ed.). New York, NY: HarperCollins.

Wickens, C. D. (1999). Frames of reference for navigation. In D. Gopher & A. Koriat (Eds.), Attention and performance (Vol. 16, pp. 113-144). Orlando, FL: Academic Press.

Wickens, C. D. (2003, in press). Aviation displays. In P. Tsang & M. Vidulich (Eds.), Principles and practices of aviation psychology (pp. 147-199). Mahwah, NJ: Lawrence Erlbaum Publishers.

Wickens, C. D., & Andre, A. D. (1990). Proximity compatibility and information display: Effects of color, space, and objectness of information integration. Human Factors, 32, 61-77.

Wickens, C. D., & Carswell, C. M. (1995). The proximity compatibility principle: Its psychological foundation and its relevance to display design. Human Factors, 37(3), 473-494.

Wickens, C.D., Helleberg, J., & Xu, X. (2001). Pilot maneuver choice and workload in free flight. Proceedings of the 11th International Symposium on Aviation Psychology. Columbus, OH: The Ohio State University.

Wickens, C. D., & Hollands, J. (2000). Engineering psychology and human performance (3rd ed.). Upper Saddle River, NJ: Prentice Hall.

Wickens, C. D., Liang, C. C., Prevett, T., & Olmos, O. (1996). Electronic maps for terminal area navigation: Effects of frame of reference and dimensionality. The International Journal of Aviation Psychology, 6(3), 241-271.

Wickens, C. D., & McCarley, J. S. (2001). Attention-situation awareness (A-SA) model of pilot error (Final Technical Report ARL-01-13/NASA-01-6). Savoy, IL: University of Illinois, Aviation Research Lab.

Wickens, C. D., & Prevett, T. T. (1995). Exploring the dimensions of egocentricity in aircraft navigation displays: Influences on local guidance and global situation awareness. Journal of Experimental Psychology: Applied, 1(2), 110-135.

Wickens, C. D., Todd, S., & Seidler, K. (1989). Three-dimensional displays: Perception, implementation, and applications (Technical Report ARL-89-11/CSERIAC-89-1). Savoy, IL: University of Illinois, Aviation Research Laboratory (also CSERIAC SOAR 89-001, Crew System Ergonomics Information Analysis Center, Wright-Patterson AFB, OH, December).