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Abstract
Angle of Attack is an important aeronautical concept used to understand the aerodynamic performance of an aircraft during different flight stages. The Federal Aviation Administration has indicated the importance of developing and encouraging the use of AOA based systems to increase flight safety. This study examined the usability of three different AOA indicators. The goal was to identify which of these indicators is better suited for student pilot training. Instructor pilots were recruited for a series of flights, in which they were asked to perform different maneuvers while using AOA indicators. The data show significant differences between the indicators with a general preference for a vertical representation of AOA.

Keywords
Angle of attack, flight instruments, visual displays, pilot training, usability

Introduction
Angle of attack (AOA) is an important concept used to understand basic aerodynamic principles in aviation, as well as to understand some aspects of an aircraft's performance capabilities (Boeing, 2000). In its simplest form, it could be defined as the angle at which the aircraft's wing chord lines meet the relative wind (the direction of the airflow with respect to the airfoil) (Federal Aviation Administration [FAA], 2008; Flach, Patrick, Amelink, & Mulder, 2003). As the wing's AOA increases, the pressure difference between the upper and lower sections of the wing will be higher (FAA, 2012; Sadraey, 2013). If the AOA is too high, a separation of airflow from the wing is produced; this separation of airflow causes the wing to stall (FAA, 2000).

In General Aviation (GA), the use of AOA indicators is almost nonexistent and most GA aircraft lack such an indicator. Even though the concept of angle of attack has been around since the beginning of aviation (Langewiesche & Collins, 1972; Aarons, 2006), and is currently widely used by military pilots, especially naval aviators (Aarons, 2006; Boeing, 2000; Dunn, 2011), its importance among GA pilots has been undervalued or simply ignored due to lack of knowledge and/or training on the value of the information a dedicated AOA indicator can provide to airmen (Aarons, 2006; Flach et al., 2003). Even though airspeed is used as a primary source of information for pilots to measure the aircraft's capabilities, it is important to note that "a stall can occur at any airspeed, in any attitude, at any power setting" (FAA, 2000, p.1); the FAA's Supplement # 1 to the Upset Recovery Training Aid (2008) mentions that even though an airplane is in a descending pattern with ample airspeed, the wing surface could potentially stall if the AOA is greater than the stall angle for the wing setting. The FAA warned that a stall cannot be avoided unless the aircraft's AOA is reduced.

A dedicated instrument that informs pilots of the aircraft's current AOA and how close the aircraft is to stalling should be considered of great importance. Even though an AOA indicator may be useful at different flight stages, it is most valuable during those stages in which the aircraft is at an AOA closer to stall (e.g., landings, go arounds, and take offs) (Boeing, 2000; Dunn, 2011, FAA, 2000; Hoadley & Vanderbok, 1987). Despite the importance that the aviation community has given to airspeed over AOA, the FAA has stressed that (a) it is important to train GA pilots on the concept of AOA and its potential benefit in understanding aircraft performance capabilities, and (b) the importance to manufacture AOA indicators that can be afforded by the GA community (FAA, 2012).

This new interest in training pilots on the use of dedicated angle of attack indicators and making these instruments easily available to them is due to the fact that at least 40% of the accidents in GA between 2001 and 2010 were related to loss of control-in flight (LOC-I) (FAA, 2012). According to the FAA (2015), LOC-I is the number one cause of fatalities in general and commercial aviation. LOC-I is defined as "an extreme manifestation of a deviation from intended flightpath," including stalls and spins (International Civil Aviation Organization [ICAO], 2013, p. 13). For this reason, the FAA's General Aviation Steering Committee (2012) recommended that in order to reduce the risk of potential stalls resulting in LOC-I related accidents, the GA community should install and use AOA systems to aid pilots in identifying aircraft stall margins. The FAA (2000) has also emphasized the importance of flight instructors being capable of providing stall training to future pilots. Due to the benefits that an understanding of AOA has on avoiding LOC-I incidents and accidents, exposing student pilots (SP) to the AOA concept and making it a meaningful aspect of their training should be considered a priority.

In recent years, avionics manufacturers have started producing and marketing AOA indicators intended for GA use. Even though a goal of an AOA indicator is to aid pilots in identifying stalling margins, some of these manufacturers may not recognize the importance of applying proper visual display design principles to their AOA indicators (for a review on visual design principles see Jimenez, Faerevaag, & Jentsch; 2016). Since pilots depend on avionics to fly their aircraft in a safe manner (Hamblin, Miller & Naidu, 2006), it is important that aviation information systems not only comply with regulations, but also provide reliable information in a user-friendly manner (Jimenez, et al., 2016; Schvaneveldt, Beringer & Leard, 2003; Woods, 1991). This enables pilots to react to the displayed information in a timely manner, while using as few cognitive resources as possible (Zhang, 1997). Instruments used to teach and familiarize pilots with AOA should comply with certain design characteristics. Wickens, Gordon-Becker, Liu and Lee (2004) discussed the importance of visual displays and their characteristics. One of the important features that makes displays user friendly is the discriminability of the elements presented by the display. In the case of AOA indicators, it is important that an indicator clearly informs the pilot when the aircraft is at a high, low, or optimum AOA. Another important characteristic includes the principle of the moving part or the dynamics of the information presented by the display; moving elements presented on the display should match the mental model and expectations of the pilot (Roscoe, 1968). Tlauka (2004) explained that the visual relationship between displays and controls should be considered in their spatial functional relationship and that a compatible display-control arrangement could enhance performance and increase user satisfaction. It is important that the information presented by the AOA indicator matches the pilots' expectations, helping them to react in a proper way and in a timely manner to the information provided by the instrument. Acemyan and Kortum (2012) discussed the relationship between usability and trust; the more usable the system is, the more an operator will trust it given that the system provides reliable information. On the other hand, poorly designed systems with low levels of usability will more likely be misused or disused, forcing users to keep their current working methods (Chamorro-Koc, et al., 2009; Maguire, 2001), regardless of how accurate the system's output is.

Three different types of AOA indicators were selected for this study. In essence, they all provide the same information, but the way the information is presented to pilots differs (vertically vs. horizontally, many round lights vs. few lights, and different symbols).

The first indicator is a vertical bar indicator, the second is a horizontal bar indicator, and the last one is a Legacy indicator (also a type of vertical indicator). It is important to note that the selected indicators were not fully integrated into the aircrafts' systems. This means that the indicators were not able to recognize different configurations such as flaps during different flight stages. Therefore, the instruments were calibrated to a specific configuration. Specifically, the pilots had to learn and memorize different light combinations presented by the AOA indicators according to different configurations of the aircraft in order to identify the proper AOA for any given maneuver.

Hypotheses

Three hypotheses were developed and tested during the experiment; these statements are related to pilot's preferences:

$H_1 1$: There is a significant difference between the indicator that presents AOA information in a horizontal fashion and indicators that present AOA in a vertical fashion.

$H_1 2$: There is a significant difference between the vertical bar indicator and the Legacy indicator.

$H_1 3$: The current location where the AOA indicator is placed (to the left of the magnetic compass on the dashboard) will be disliked by Instructor Pilots (IPs).

Methodology

This study employed subjective measures to ask participants about their opinion of the AOA indicators used in this study. The experiment was conducted in the operational environment in which pilots perform their work on a daily basis.

Sample

Nielsen and Landauer (1993) suggested that in order to detect most usability issues in a small project, a sample size of around *N* = 7 would suffice. Sample sizes higher than that would add little to the identification of design issues of a given interface. For this particular study, 10 IPs (9 male and 1 female) were recruited to participate. The average age was 22.3 years (*SD* = 3.2). The average total flight time of the participants was 424 (*SD* = 111.3) with an average experience of performing the duties as an IP of 141.5 hours (*SD* = 120.7). None of the participants had experience as a military pilot, and none of the participants had previous experience with AOA indicators.

Apparatus and Materials

Three Cessna 172S aircraft equipped with the Garmin G1000 glass flight deck were used for the study. Each aircraft was equipped with one of the three AOA indicators (Figure 1). All indicators were manufactured by Alpha Systems, Inc. The first aircraft was equipped with an Ultra 2.50" bar indicator installed vertically (L: 2.50", W: 0.75", D: 1.00"); the second one with an Ultra 2.50" (L: 2.50", W: 0.75", D: 1.00") bar indicator installed horizontally; and the third aircraft with a "Legacy" indicator (L: 2.50", W: 0.87", D: 1.25") installed vertically. Both bar indicators consisted of a series of lights that were aligned either vertically or horizontally; each of these indicators had a total of 16 round lights (5 red, 1 blue, 6 yellow, and 4 green). The Legacy indicator had fewer lights (1 red chevron, 2 green semicircles forming a "doughnut", 1 yellow chevron, and a blue line). The vertical bar and Legacy indicators were installed approximately 3 inches to the left of the magnetic compass. The horizontal bar indicator was aligned with the magnetic compass and it was placed on the instrument panel, approximately 2 inches below the magnetic compass.

Figure 1: The three AOA indicators used in the study. Vertical bar, horizontal bar, and legacy indicators. Adapted from Alpha Systems, (2010).

There are differences in the way the indicators display AOA information. For instance, during slow flight and landing flare, the bar indicators (both horizontal and vertical) illuminated all red lights plus the blue light. On the other hand, the Legacy indicator illuminated the green doughnut. For cruise, climb, and final approach, the bar indicators displayed all red, one blue, and all yellow lights, while the Legacy indicator displayed the bottom half green doughnut and yellow chevron.

During a stall warning, the bar indicators displayed all red lights, while the Legacy indicator displayed the red chevron and the top half of the green doughnut.

A pre-flight questionnaire designed to collect demographic information, as well as previous experience using AOA indicators, was used prior to the experimental portion of the study. In order to capture the participants' opinions on the usability of the AOA indicators, a post-flight questionnaire was developed. This questionnaire included an adaptation of the Systems Usability Scale (SUS) (Brooke, 1996). A series of surveys were created in order to ask IPs about their opinions concerning visual representation and location of the instrument inside the cockpit, effect of the AOA indicator in performing maneuvers, and perceived advantage of the instrument for pilot training. Table 1 shows a sample of questions asked for each survey.

Table 1: Sample Questions presented on the Post-Flight Questionnaire

Survey Section	Question	7 Point Scale range
Visual representation and location	This particular AOA indicator's visual representation of AOA was intuitive and easy to understand	Strongly Disagree- Strongly Agree
	This particular AOA indicator's orientation (horizontal/vertical) was well suited for a visual representation of AOA	Strongly Disagree- Strongly Agree
	This particular AOA indicator's physical location in the cockpit facilitated a crosscheck of AOA	Strongly Disagree- Strongly Agree
Maneuvers	I think that crosschecking this particular AOA indicator enhanced my personal performance on the following maneuvers*	Not at All- Extremely
	This particular AOA indicator enhanced my awareness of how close the aircraft is to a stall at all times during the following maneuvers*	Not at All- Extremely
	During the following maneuvers, I crosschecked this particular AOA indicator*	Not at All- Very Frequently
	I feel that crosschecking this particular AOA indicator helped me in flying a more stable approach on final during the following maneuvers**	Strongly Disagree- Strongly Agree
	I feel that crosschecking this particular AOA indicator enhanced my landing performance during the following maneuvers**	Strongly Disagree- Strongly Agree
Instructor Pilots	I can see advantages of this particular AOA indicator for training student pilots in flight	Strongly Disagree- Strongly Agree
	I think this particular AOA indicator can improve student's conceptual understanding of AOA	Strongly Disagree- Strongly Agree
	I would integrate this particular AOA indicator in my training of student pilots	Strongly Disagree- Strongly Agree
Overall Satisfaction	Overall I would rate my experience with this particular AOA indicator as	Worst Imaginable- Best Imaginable

* Individual questions were asked for Slow-Flight, Power-On Stalls, Power-Off stalls, Normal Approach and Landing, and Short-Field Approach and Landing.

** Individual questions were asked for Normal Approach and Landing, and Short-Field Approach and Landing.

Design and Procedures

This was a within-subjects study. Each participant was exposed to all three AOA indicators. In order to reduce learning bias and carryover effects, the presentation of the instruments was counterbalanced.

The study was divided into four different sessions, and the study had an approximate duration of two weeks. The first portion was an informative/training session. After the briefing, participants filled out the pre-flight questionnaire and received a one hour training session. The training consisted of a brief explanation of the AOA concept and an introduction to the functions embedded in the indicator. Participants were given a copy of the approximate indications form, which told pilots what information the instrument would show on each of the flight maneuvers they would be performing during the three experimental sessions.

Each of the experimental sessions had an approximate duration of one hour. Each flight was divided into five different stages in which participants were to use the assigned AOA indicator to aid them in performing each maneuver. The five maneuvers selected for this study were slow flight, power-on stall, power-off stall, normal approach and landing, and short-field approach and landing. After the first flight, participants filled out the first post-flight questionnaire. The same procedure was used for flights two and three of the experiment.

Results

The different subjective scales containing Likert items were analyzed using a repeated measures analysis of variance (ANOVA) with a Greenhouse-Geisser correction. Any significant differences were followed up with a pairwise comparison of the means using a Bonferroni correction. In total, six subsections were analyzed using this method (Table 2).

Table 2: ANOVAs with Greenhouse-Geisser Correction and significant pairwise comparisons for subsections of the Survey administered to participants after each flight.

Survey Section	Max. Possible Score	Indicator Type	Mean	Std. Dev.	Significance	Significant Pairwise Comparisons
Systems Usability Scale (SUS)	100	Horizontal	45.69	27.58	*n.s.*	N/A
		Vertical	61.11	24.25		
		Legacy	71.11	19.07		
Visual Representation	21	Horizontal	10.11	3.85	$F(1.79, 14.34) = 7.39$, $p < 0.05$	Horizontal – Legacy*
		Vertical	15.78	4.94		
		Legacy	17.78	2.11		
IPs Enhanced Performance	35	Horizontal	17.22	7.43	$F(1.27, 10.21) = 4.73$, $p < 0.05$	Horizontal – Vertical*
		Vertical	21.22	6.26		
		Legacy	22.33	6.18		
Enhanced Stall Awareness	35	Horizontal	19.50	7.06	$F(1.70, 15.32) = 6.48$, $p < 0.05$	Horizontal – Vertical* Horizontal – Legacy*
		Vertical	23.40	5.98		
		Legacy	24.70	5.54		
Crosschecked Indicator During Maneuvers	35	Horizontal	18.00	6.78	$F(1.25, 8.77) = 5.29$, $p < 0.05$	N/A
		Vertical	22.62	6.07		
		Legacy	23.75	6.86		
Indicator would Enhance Student Performance	35	Horizontal	18.78	8.24	$F(1.37, 10.98) = 5.29$, $p < 0.05$	N/A
		Vertical	22.56	6.17		
		Legacy	24.11	5.64		

*significance, $p < 0.05$

Subsections inquiring about the "visual representation of AOA", the indicator's "ability to enhance IPs' personal performance", "enhanced stall awareness", "crosschecking indicator during maneuvers", and "crosschecking the indicator would help would help SPs enhance their performance during maneuvers" were significant. Significant differences between indicators when using a pairwise comparison were found on "visual representation of AOA", the indicator's "ability to enhance IPs' personal performance", and "enhanced stall awareness." Mean scores for the SUS were not significant. It is important to note that in the section related to the "indicator's ability to enhance IPs' personal performance" the mean difference between the horizontal bar indicator and the Legacy indicator (not significant) is greater than the mean difference between the horizontal bar and the vertical bar indicator (significant). This inability to find a significant difference between the horizontal bar and the Legacy indicator is believed to have occurred due to the difference in variance between the two samples

The Friedman's rank test for correlated samples was used to analyze five individual items that were of special interest for the study. Table 3 shows the results of the analysis. In this particular case, a lower rank in the test signifies a better score given by participants to that specific indicator. The items "Crosschecking Indicator Enhanced Landing Performance (Normal Approach and Landing)", "Crosschecking Indicator Enhanced Landing Performance (Short Field Approach and Landing)", and "Overall Satisfaction with Indicator" were significant.

Table 3: Friedman's rank test for correlated samples used to analyze six individual items

Item	Sig.	Indicator Type	Mean Rank
Crosschecking the Indicator helped in Flying a More Stable Approach on Final (Normal Approach and Landing)	n.s.	Horizontal Bar	1.56
		Vertical Bar	2.06
		Legacy	2.39
Crosschecking the Indicator helped in Flying a More Stable Approach on Final (Short Field Approach and Landing)	n.s.	Horizontal Bar	1.78
		Vertical Bar	1.83
		Legacy	2.39
Crosschecking Indicator Enhanced Landing Performance (Normal Approach and Landing)	$\chi^2_F(2) = 11.08$; $p < 0.01$	Horizontal Bar	1.33
		Vertical Bar	2.00
		Legacy	2.67
Crosschecking Indicator Enhanced Landing Performance (Short Field Approach and Landing)	$\chi^2_F(2) = 8.82$; $p < 0.05$	Horizontal Bar	1.56
		Vertical Bar	1.83
		Legacy	2.61
Overall Satisfaction with Indicator	$\chi^2_F(2) = 6.06$; $p < 0.05$	Horizontal Bar	1.40
		Vertical Bar	2.25
		Legacy	2.35

Comments participants provided during the experimental stage of the study were collected as well. IPs had the option to provide their own thoughts for each of the items on the post-flight questionnaire. In total, 576 comments were collected. There were 163 comments about the horizontal bar indicator, 221 about the vertical bar indicator, and 192 comments for the Legacy indicator. Two raters independently coded each comment into one of four different categories: positive, negative, mixed, and other comments. Examples of positive comments include, "[it] would help in setting proper climb angle after recovery" or "good location and representation, the lights are easy to understand." Examples of negative comments include, "hard to integrate into scan" or "the indications are not that simple. May require frequent review for students." Examples of mixed comments include, "I like the number of red lights. Like counting down until stall, but so many yellow and green, too complex, sometimes all light up during/after maneuvers which is just distracting" or "it really helped for landings, not so much slow flight/stalls." Examples for other comments include: "gusty crosswinds made crosschecking hard" or "Flew slow flight at MCA [minimum controllable airspeed] and got different indications from published. Flew at published indications and airspeed was 10 knots above MCA." A Cohen's Kappa was used to analyze interrater reliability. Interrater reliability was found to be Kappa = 0.80, $p < 0.001$, 95% CI (0.759, 0.842).

The number of comments in which both raters agreed on was separated according to the type of indicator. For the horizontal bar indicator, raters agreed on 147 of the 163 comments. For the vertical indicator, raters agreed on 189 of the 221 comments. For the Legacy indicator, raters agreed on 164 of the 192 comments. Figure 2 shows the interrater agreement by indicator type. Comments about indicator location (37 in total) were also analyzed. Figure 3 shows interrater agreement on location by indicator.

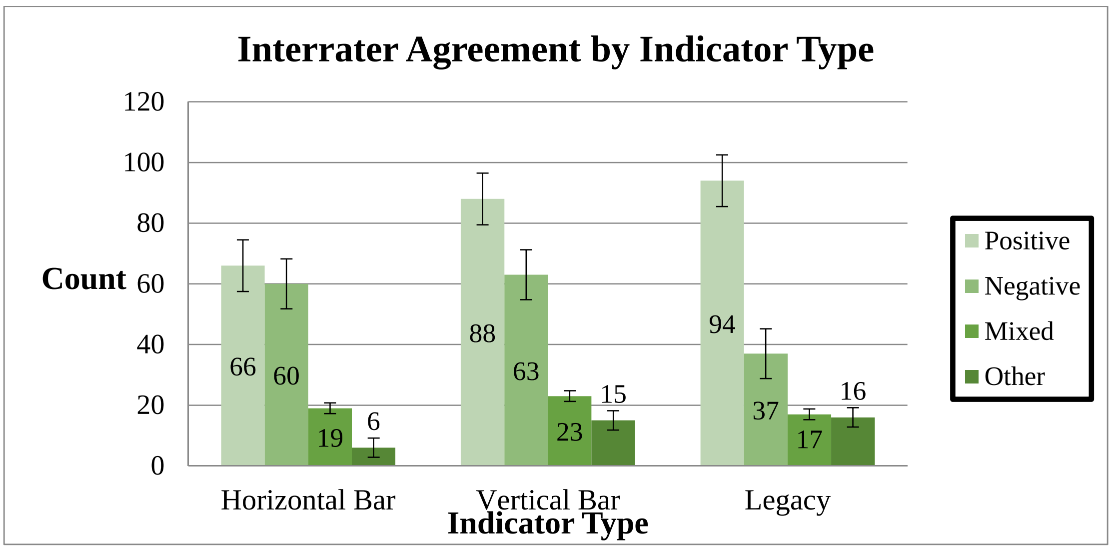

Figure 2: Indicator type separated by type of comment.

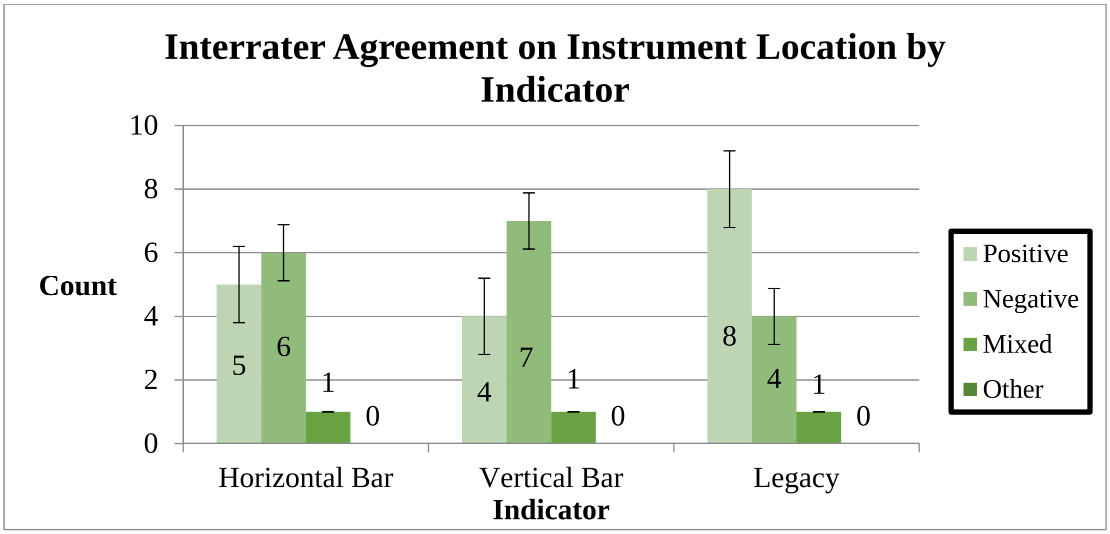

Figure 3: Instrument location in the cockpit by indicator.

Conclusion

The results allowed researchers to test three hypotheses. The first hypothesis stated that there is a significant difference between the indicator that presents AOA information in a horizontal fashion and indicators that present AOA in a vertical fashion. It can be concluded from the data analysis that pilots overall preferred vertical AOA indicators over the horizontal bar indicator. Significant differences between the horizontal bar indicator and at least one of the vertical indicators were found on six of the eleven statistical analyses (comments not included). The significant differences were found for visual representation (Legacy), Enhanced performance (vertical bar), enhanced stall awareness (vertical bar and Legacy), enhanced landing performance for normal approach and landing (Legacy), enhanced landing performance for short field approach and landing (Legacy), and overall satisfaction with the indicator (Legacy). The horizontal bar indicator had the lowest score on all of the subsections of the post-flight questionnaire, including the SUS in which it achieved a mean score of 45.69 compared to the legacy indicator (71.11), and the vertical bar indicator (61.11). The results of the statistical analysis of the Likert items on the post flight questionnaires are in accordance with the number of positive versus negative comments that participants gave to each indicator. The reasons why participants liked vertical indicators better than the horizontal bar indicator were evident. When commenting about the horizontal bar indicator, one of the participants stated, "when pitching for angle of attack we use the vertical plane. Horizontal display counter-intuitive." Another participant commented, "total negative transfer of learning, horizontal indication has no relevance to pitch."

In contrast, some of the comments about the vertical indicators support the idea that the indicator should match the pilot's mental expectations. For example, one participant commented about the vertical bar indicator stating, "the vertical bar represents the vertical force making it simple to understand." These comments are in accordance with visual display design principles and the principles of pictorial realism and the principle of congruency of dynamic information. Wickens et al. (2004) discussed the importance of designing displays that comply with the mental models and expectations of the operator, this includes having realistic visual representations of the information that is intended for the operator. These comments are also in accordance with the importance of designing visual displays that take into consideration the display-control arrangement (Tlauka, 2004). As it was mentioned several times in the comments, pilots preferred the vertical displays because they match their mental expectations and because the way the controls need to be applied in order to increase or decrease AOA is congruent (by pulling or pushing the yoke or stick). A horizontal bar indicator violates both mental models and expectations of the pilot and the idea of a synchronized display-control arrangement.

The second hypothesis stated that there is a significant difference between the vertical bar and legacy indicators. The analyses do not support this hypothesis. It is important to mention though that for the eleven sections of the post-flight questionnaire, the Legacy indicator obtained the highest mean scores and the smallest standard deviations on all of the repeated measures analyses. On the Friedman's rank test for correlated samples, the Legacy indicator ranked higher than the vertical indicator on eight sections ("visual representation", "enhanced performance", "would enhance students' performance", "helped in flying a more stable approach on final [normal and short field]", "enhanced landing performance [normal and short field]," and "overall satisfaction". The Legacy and vertical bar indicators had the same rank on two sections (system usability scale, and enhanced stall awareness). The vertical bar indicator achieved a higher rank in only one category (crosschecked indicator during maneuvers). The number of positive comments also favors the Legacy indicator (94), compared to the vertical indicator (88). The number of negative comments for the Legacy indictor is approximately half of the total number of negative comments for the vertical indicator (37 versus 63). Most of the negative comments for the vertical indicator refer to the high number of lights used for each of the indications. One of the comments that best reflects how most participants felt about the vertical bar indicator's light arrangement and indications was provided by one of the participants when asked about his overall experience with the indicator. The participant stated that "the indicator uses too many lights and can be distracting, especially on takeoff and climbout. Also when transitioning from cruise to higher AOA, the sudden illumination of all 16 lights from just one green would grab my attention, which I did find distracting." Negative comments about the Legacy indicator were not as consistent. A few participants complained about the symbols and the number of lights on the indicator. One example includes, "Colors/symbols less intuitive compared to light bar indicator." Positive comments for the vertical indicator concentrated on the fact that the indicator was easier to understand and more intuitive than the horizontal bar indicator. Some other positive comments emphasized the ability of the indicator to help participants to perform maneuvers in an efficient manner, and to support decision-making. Some examples include, "I felt more confident with a higher AOA and slower airspeed during final approach," and "complemented maintaining slow flight." For the Legacy indicator, positive comments in general focused on the simplicity of the indications and the discriminability of the lights displayed on the indicator (chevrons and doughnut) compared to the multiple lights on the bar indicators. Some examples include, "Very simple, clean, and quick to read," and, "with different symbols, it was much easier to see critical AOA in peripheral vision." Positive comments about the Legacy indicator also referred to the indicator's ability to support decision making and improve performance: "allows me to know I am on speed quickly without having to look down at airspeed," and "if the normal indication [green doughnut] wasn't there, I knew something had changed." Most participants commented on how useful the Legacy indicator was during landings. Some comments that best describe what participants thought about the instrument during landing maneuvers include, “Helps to not overcorrect on pitch changes, keep the ball [green doughnut] and the airplane lands super smooth,” and “in these landings I was less apprehensive about my slower airspeeds during final approach, I also knew I was doing it correctly because of the green doughnut.” For comments regarding the overall experience with the indicator (in which all participants commented), independent raters agreed on 6 positive comments for the Legacy indicator versus 1 positive comment for the vertical indicator. Both indicators received one bad comment; for mixed comments, the Legacy indicator received 2 comments versus 5 for the vertical bar indicator. Even though the statistical analyses failed to support our hypothesis that there was a significant difference between the vertical bar and Legacy indicators, the high number of negative comments received by the vertical bar indicator suggests that participants felt more comfortable flying with the Legacy indicator.

The third hypothesis stated that the current location where the AOA indicator is placed, to the left of the magnetic compass on the dashboard (vertical bar and Legacy indicators) and below the magnetic compass (horizontal bar indicator) would be disliked by IPs (Figure3). This hypothesis was not supported by the results of the experiment. One item on the post flight questionnaire asked participants if the particular AOA indicator’s physical location in the cockpit facilitated a crosscheck of AOA. This was a seven point Likert item that ranged from strongly disagree to strongly agree. The horizontal bar indicator received 3 negative ratings (below 4 on the Likert Scale), 1 neutral rating (4 on the scale), and 6 positive ratings (5 or higher on the scale). The vertical bar indicator received 1 negative rating, and 8 positive ratings. The Legacy indicator received 1 negative rating and 9 positive. This means that across indicators, participants acknowledged that the indicators’ current location facilitated the crosscheck of AOA. On the other hand, the analysis of the comments indicated that there was a high number of negative comments (Figure 2). It is interesting to see how the vertical bar indicator received the highest number of negative comments and the lowest number of positive comments while the comments for the Legacy indicator seems to be consistent with the ratings it received on the Likert item discussed above. Comments for the horizontal bar indicator also seem to be inconsistent with ratings received on the Likert item. Most pilots only talked about minor modifications to the current location of the instrument. Only one participant suggested a major change to the instrument’s location. This participant stated that the indicators “should be aligned with AS [airspeed] tape”. This is an interesting comment as the airspeed tape is on the left side of the G1000 display on the pilot’s side of the cockpit. As stated by the FAA (2013), “if not otherwise authorized or directed by the tower, pilots of fixed-wing aircraft approaching to land must circle the airport to the left.” These types of maneuvers require pilots to check for other aircraft in the area while checking the aircraft’s position in reference to the runway (which is normally to their left).

It can be concluded that vertical indicators are better representations of AOA because they support the expectations and mental models of pilots. The horizontal bar indicator is counterintuitive and it can create confusion, especially for SPs who do not fully understand all the aeronautical concepts related to flying. Even though the statistical analyses did not show a significant difference between the vertical bar and Legacy indicators, it can be concluded, according to the comments provided by participants, that the Legacy’s simple display design aids pilots to perform landing maneuvers better. The reason why the Legacy indicator seems to be a better instrument is because it relies more on perception than on higher order mental processes. While the Legacy indicator displays few lights and different shapes, the vertical bar indicator relies on a series of 16 lights that almost force pilots to count the number of red lights remaining to know how close they are to stalling. The Legacy indicator on the other hand, shows fewer indications making it easier and more intuitive for pilots to read the display. The Legacy's visual layout seems to be in accordance with compatible display-control arrangements discussed by Tlauka (2004) and with Kornblum et al.'s (1990) dimensional overlap model; which claims that when a stimulus-response ensemble shares a number of characteristics, the stimulus can trigger an automatic response due to the similarities between the stimulus and the mental expectations of the operator. On the other hand, some pilots commented on the vertical bar indicator during the stalls and slow flight maneuvers; they liked counting the lights or seeing the lights disappear as they were approaching the critical AOA until stalling. This exercise (counting lights) requires the utilization of multiple cognitive resources, including memory. This would indicate that during these types of maneuvers in which the aircraft is a few thousand feet above the ground, pilots can afford to count lights in order to know when a stall would happen; they would have plenty of time to recover from a stall without worrying about flying into the ground. This same approach is both inefficient and dangerous during landings because pilots cannot waste time or cognitive resources on counting lights in order to determine the aerodynamic status of the aircraft. During landings pilots need to be aware of multiple cues inside and outside the cockpit. Some participants commented how they decided to disregard the vertical bar indicator while landing. On the other hand, the Legacy indicator received positive comments about its ability to assist pilots during landings. The few indications and the different shape of the symbols on the display can effectively inform pilots of the aerodynamic status of the aircraft. There is no counting lights involved, only perception; a red chevron pointing downwards informs pilots to decrease AOA and a full green doughnut tells the pilot the aircraft is in a safe aerodynamic state for landing or high-performance maneuvering.

As for the location of the indicator inside the cockpit, it is unclear whether or not pilots favored the present location. Both bar indicators received a high number of negative comments, while the Legacy indicator received a high number of positive comments and very few negative ones. It is important to remember that the types of negative comments for the indicators only mention minimum modifications to the indicator's location. It can be speculated that the reason why participants favored a central location of the instrument rather than a leftward position was because perhaps they disregarded the indicator during most parts of the traffic pattern, and only focused on it during final approach and landing when the aircraft was already aligned with the runway. This same reasoning could be applied to slow flight and stalls; pilots did not necessarily need to scan for traffic by looking to the left of the aircraft, and while performing the maneuvers they were looking forward and outside the cockpit. This would explain the high ratings on the Likert item that asked participants about the current location of the instrument inside the cockpit. Nevertheless, the difference in the number of positive and negative comments for the location suggests there might be a relationship between indicator type and its location.

Based on the analyses of the data and visual display design principles, it could be inferred that the Legacy indicator is the most usable indicator in comparison with the Ultra 2.5" bar indicators (vertical and horizontal). The results show a significant difference between the Legacy indicator and the horizontal bar indicator in six of the eleven analyses, including overall satisfaction with the indicator. Even though the statistical analyses did not show a significant difference between the vertical bar and Legacy indicators, the difference in the number of negative comments between the two (66 for the vertical bar vs. 37 for the Legacy), and the nature of the positive comments for the Legacy indicator, shows that participants, in general, preferred the Legacy indicator.

Limitations and future research

The present study has a number of different limitations that should be addressed in future studies. The first limitation we encountered was the nature of the sample, participants were relatively inexperienced IPs. Maybe using experienced IPs could help to clarify if there is a significant difference between vertical indicators; at the same time, more experienced participants could have a different opinion about the location of the indicator in the cockpit. Perhaps a study with a larger sample that combines both types of pilots could help to clarify differences between experienced and inexperienced IPs. Another limitation of the present study was the type of data collected. Due to time limitations, our study was constrained to collecting subjective data. Future studies should consider using objective measures. For instance, it is possible to collect flight data from the fleet of Cessna 172S. This data, if properly analyzed, could help researchers understand if there is a clear relationship between indicator preference and performance. Another important limitation of the study was the location of the indicator in the cockpit; it would be interesting to manipulate the location of the instrument in order to see if participants blindly agree with the location of the instrument, or if on the other hand, they suggest a different location for the instrument based on their past experiences and aviation knowledge. Finally, having SPs' perspective on AOA indicators should be considered. A study using SPs would help researchers better understand the preferences and needs of SPs while using AOA as part of their training.

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