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DISPLAYS

The performance and workload effects of task re-location during automation

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Abstract

We report an experiment which investigated the performance and workload effects associated with the functional grouping of automated displays in a multi-task flight simulation. Eleven rated pilots performed tracking, systems monitoring, and target acquisition sub-tasks in manual conditions and when the targeting task was automated. In the latter condition, the target acquisition display was relocated either proximally, distally, or neutrally with respect to the functionally similar, systems monitoring display. It was hypothesized that an automated task display relocated near its functional equivalent (the proximal condition) would result in increased performance efficiency and lower perceived workload compared to the other relocation positions. An advantage for adaptive automation was confirmed with pilots exhibiting less tracking error, lower monitoring response times, lower target response times, and increased percentage of target responses during automated compared with manual conditions. Results did not confirm the hypothesized benefits for display location. However, when interpreted within the Proximity Compatibility Principle framework where both perceptual and processing proximity are recognized, results confirmed an advantage for the functional grouping layout of the display. Specifically, the proximal grouping condition was the only condition that resulted in both performance and workload benefits. Some observations on the implications for display design in systems using automation are provided.

Keywords: Display layout; Adaptive automation; Proximity Compatibility Principle (PCP)

1. Introduction

As aviation systems evolve and become more complex, questions concerning technology and the pilot's role are constantly brought to the fore [1–4]. Technological advances in flightdeck display capabilities, coupled with the greater flexibility of electronic display options, have increased both the volume and processing demand of avionics displays. These larger demands have served as a rationale for the implementation of automated systems which, in turn, have forced a re-conception of the pilot's role. There is a marked shift from the view of the pilot as momentary hands-on controller, towards the pilot as system manager, system monitor, button pusher or system 'baby-sitter' [5–7]. Pilots may not relish their portrayal as systems managers but the information needs of the current flightdeck largely define the flying role. As Wickens and Carswell [8] pointed out, the information needs of the airline pilot are clearly multidimensional, considering that the aircraft has six degrees of freedom of motion and information pertaining to these may originate from a variety of display sources.

In general, the goal of flightdeck display design is to make flight-relevant information available to the pilot. When flightdecks were gauge and dial environments the designer's task was to determine 'what' information was to be displayed, 'how' to display it, and 'where' physically to install the display mechanism. The emphasis was on the 'what' and the 'how', but the 'where' was often constrained by the physical limitations of cockpit space. When glass cockpit technology was introduced, suddenly the 'where' possibilities exploded, displays could be placed wherever there was screen. Display layout had always been considered by designers but the glass cockpit signaled a new emphasis on the delineation of layout principles and guidelines for avionics. Arguably, the simplest layout principle was a functional one, where displays that are related should be grouped close together. Simply stated, the classic principle of functional grouping dictates close proximity between functionally related instruments. This design principle has been espoused for

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general display design [9,10] and has been successfully practiced in the layout of aircraft instruments [11,12].

Recently, Wickens and Carswell [8] have refined these concepts into the Proximity Compatibility Principle (PCP) which examines how sources should be placed with respect to one another and how they should be organized. It should be clear that PCP is not a theory but, rather, is based on a set of theoretical principles of human information processing that bear on the 'where' aspect of the display designer's task [8]. The PCP is presented as a guideline to use in determining where a display should be located, given its relatedness to other displays.

Our interest in the PCP is in the functional grouping of tasks, especially in multi-task environments. Functional similarity refers to the similarity of the units or objects being measured, as represented in the operator's semantic space [8]. For example, all indicators of a given class of information (e.g., all warning indicators) would be said to define high functional similarity. We have been examining functional grouping in a new form of automation called adaptive automation. Adaptive automation is a human-centered task allocation strategy in which the control of tasks shifts dynamically in real-time, based upon the changing task demands imposed on the operator [13,14]. This adaptive strategy is a response to the perceived loss of control inherent in a traditional automation strategy where the capabilities of the human versus the machine are compared and tasks are allocated for extended periods based on this comparison [15].

Adaptive automation introduces a number of relevant issues pertinent to the PCP. It is important to understand that the control of a particular task may shift between the pilot and the system a number of times, depending on changing taask demands. Thus, unlike traditional automation, control of a task can also be returned to the operator, even if task demand had previously been great enough to warrant loss of control. This is important because the automation of a task not only signals a shift in control, but also a change in functionality. We suppose that tasks which are adaptively automated are transformed, conceptually, to monitoring tasks because in an adaptive system the operator must always be ready to re-acquire manual control. We must, however, acknowledge that the shift in task status may also be accompanied by a shift in task load, where the automation of the task actually imposes a 'new' form of load on the operator. An example is some recent automation technologies like the 'pilot's associate', where the output of the 'associate' requires the pilot to process aural and visual warnings [16,17]. Such aids are capable of placing a different burden upon the busy pilot in terms of coordination, inquiry, and response.

The purpose of the present paper is empirically to examine the relevance of the PCP in the context of adaptive automation in multi-task systems. Specifically, we seek to understand the effects of functional grouping of displays during periods of automation. Like Wickens and Carswell [8] we consider not only the benefits of closeness but also its costs. We also assume that the effects of task automation can propagate throughout a multi-task system. Consequently, we examine performance and workload on all components of the multi-task system. Our goal is to develop layout principles for the display of alpha-numeric and graphical information to maximize pilot performance in multi-task systems which utilize adaptive allocation strategies.

2. Experimental method

2.1. *Experimental participants*

Eleven experienced pilots (ten males and one female) volunteered to participate in this study. Experienced pilots were chosen for testing in preference to naive subjects because the former have a rich expertise to guide their interaction with a full fidelity system. Conversely, naive subjects have limited experience and produce a significantly different pattern of performance from expert participants (see [18]). The pilots' mean age was 33.7 years and they had a mean flight experience of 1,278.7 hours. The majority of the pilots fly under Part 135 of the Federal Aviation Regulations. All were in professed good health at the time of testing.

2.2. *Experimental task*

An experimental test platform was constructed for the present experiment. This was the STARFIRE facility (Strategic Task Adaptation: Ramifications For Interface Relocation Experimentation), a high-fidelity test environment. STARFIRE is an extension of previous multi-task test facilities including MINSTAR [19], MINUTES [20], MATSET [21], and SCORE [22]. STARFIRE consists of tracing (psycho-motor), system monitoring (perceptual-motor), and target acquisition (cognitive) sub-tasks, representing three flight-relevant domains [23]. We view the STARFIRE battery as a higher fidelity testing environment because it combines flight relevant tasks with movement over a 3-dimensional textured environment, a critical component for evoking the feel and richness of real world flight. The fidelity itself is not the critical component but the combination of fidelity and flight relevant psychological tasks. In this manner, generalizability emerges from comparability of psychological processes in test and target environments, not from improvements in realism per se (see [24,25]). The three sub-tasks are displayed in a Heads-Up Display (HUD) mode, through which the pilot can also view a dynamic, textured flight environment. The three sub-tasks can be displayed in any of nine cardinal positions on the HUD. The sub-tasks

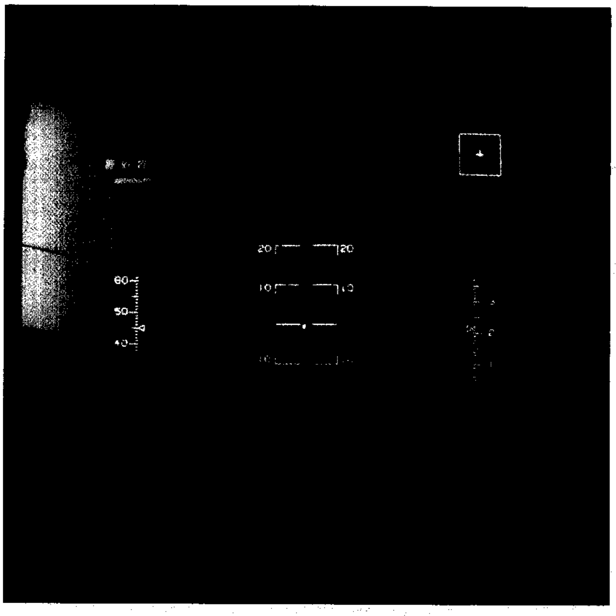

Fig. 1. The STARFIRE test battery. The system monitoring display appears in the upper left corner. The tracking display with pathway-in-the-sky is located in the middle. The target task is displayed in an automated configuration proximal to the monitoring (demonstrating the proximal condition).

can be performed singly, in combination, or under varying modes of automation as required by the experimental procedures. An illustration of the STARFIRE facility in one of its display configurations is shown in Fig. 1.

STARFIRE's tracking task is located centrally on the HUD. The tracking employs a 3-dimensional pathway-in-the-sky which serves to guide the pilot along a preselected route. It presents turns, ascents, and descents. The pathway is re-drawn each second and presents a ten second lead, Fig. 1. The flight dynamics were replicated from an actual aircraft and the 'highway-in-the-sky' conception is one which has been proposed for several forms of operation (see [26]) and is currently being employed by developers of user-interface environments (e.g. Virtual Prototypes Inc., Montreal, Canada). The pilot's goal is to center their aircraft in the path by aligning the ownship display with a moving cueball which is set five seconds in front of the pilot's ship. The tracking highway-in-the-sky was imposed upon a standard HUD symbology which most of our pilots were very familiar with even if they did not fly such HUDs in their everyday operations. The HUD information included a pitch ladder, indicating the center of the pilot's aircraft as well as dynamic pitch indication, airspeed, heading, and altitude. Actual flight control was effected using a standard F-16 flight-stick and hence both display and control functions were highly related to actual aircraft operation. While this tracking is a 3-dimensional representation, the tracking task itself can be reduced perceptually to a 2-dimensional compensatory first-order track.

STARFIRE's system monitoring task is a configuration of five lights (two green lights normally on, two red lights normally off, and one yellow bar light normally off) and four graduated sliding indicators with criterion-level indicators. The monitoring tasks chosen were an exact transfer of an EPR (Engine Pressure Ratio) display from a contemporary 747-400 and hence was a format familiar to many pilots. The goal for the pilot is to reset the lights and/or gauges whenever they deviate from their normal status. Monitoring deviations are controlled by the experimenter via programmed scripts. STARFIRE's target acquisition task requires the pilot to scan the textured surface and locate 3-dimensional targets which are either spheres, cubes, or pyramids. After a target has been detected the pilot brings up a weapons management display, selects the weapon (sphere weapon, cube weapon, or pyramid weapon), and fires the weapon. Firing a weapon always destroys the target, regardless of type. Target location, size, and type are also script specified. STARFIRE also provides capabilities to automate any of the tasks. When the target acquisition task is automated, the weapon menu is on the screen at all times while the system continuously scans the surface for targets. Upon detecting a target, the system cycles through weapons, eventually selecting one. Pilots are instructed to fire the weapon only upon confirmation of the target. Failures are initiated in the automated mode by having the system select an incorrect weapon for a particular target. Pilots may then override the automated system, return the target acquisition task to manual control, and complete the task. Fuller details of the STARFIRE facility, and especially the automation of tracking and monitoring tasks, which are options not used in the present work, are given in [27].

STARFIRE is supported on a Silicon Graphics 4D/310 VGXT Iris computer and displayed on a 35-inch Mitsubishi color monitor mounted on the front of a single seat aircraft shell. The color monitor resolution was 640 × 480 pixels and had dark tinted face glass. The viewing distance was approximately 43 inches. The interior of the cockpit contained a flight control stick and response buttons. All response buttons were illuminated and some were color-coded or number-coded to facilitate S-R mapping with their function, see Fig. 2. This entire facility was light-enclosed to prevent distraction and to reduce ambient light and glare.

2.3. Experimental measures

Tracking performance was assessed through root mean square error (rmse). System monitoring performance was measured by response time (10^{-1} s). Pilots were also assessed a 30-second response time for each missed monitoring deviation. Performance on the target acquisition task was quantified as response time and accuracy. Measures of workload were collected using the

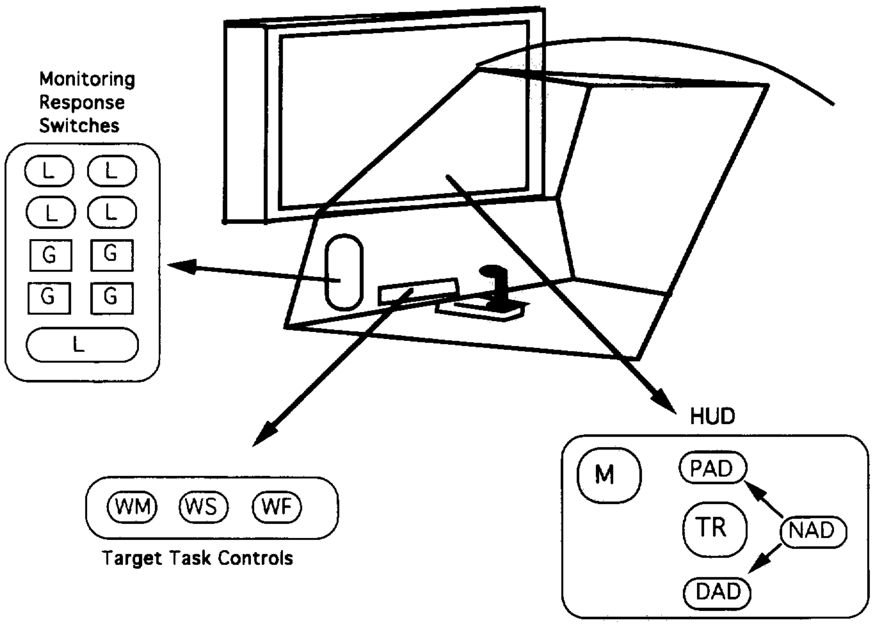

Fig. 2. Experimental Interface. The figure depicts the cockpit control switches and the HUD presentation. Each light (L) or gauge (G) in the monitoring task has its own response button. Target task controls include a weapons menu switch (WM), a weapon selection switch (WS), and a weapon fire switch (WF). The figure also depicts HUD display locations for the system monitoring (M) and tracking (TR) tasks as well as location for the neutral automated target display (NAD), the distal automated target display (DAD), and the proximal automated target display (PAD).

Subjective Workload Assessment Technique (SWAT), see [28] by having subjects respond on a three point scale to the questions: How much spare time do you have? (time load), What is your stress level?, and What is your mental effort? These dimensions are adaptations of factors proposed as major contributors to subjective workload [29]. Procedures for the administration of the SWAT were adapted according to the observations of Biers and MacInerney [30]. The SWAT was used in preference to other workload scales as it presents a minimal load in itself and, hence, can be used in real-time and with little disturbance to the primary task.

In the present experiment, we examined subjective workload in detail and a brief account of these additional procedures and assumptions is given here (for an in-depth description see [2]). In additional to the normal integer values, banded workload scores and specific workload scores were calculated. Banded workload scores represent simple addition of the integer values for the three individual SWAT dimensions. This provides a workload score independent of assumptions about which of the dimensions dominates. It is the sum from all dimensions which produces the outcome score. The banded workload score includes the modifying influence of companion integer values on each dimension. Specific workload scores are computed based upon a logical ordering of the twenty-seven response combinations with the assumption that time (T) stress (S), and effort (E) are contributors to subjective workload in the order named. While the logic of this ordering is open to dispute (see [30]) we have used the named order TSE to compute the specific workload values here.

2.4. *Experimental design*

Each pilot performed sequential trials in a within-subject design. The within-subject approach was employed to control for individual differences associated with extraneous variables such as gender, experience (e.g. civil, military), and total flight hours; variables which were not overtly controlled in the recruitment of subjects. Pilots were required to perform the STARFIRE battery in seven trials. In numbers one, three, five, and seven the pilot assumed manual control of the three sub-tasks (referred to as manual trials). In the remaining trials (two, four, and six) tracking and systems monitoring were performed manually and the target acquisition task was automated (referred to as automated trials). In one automated trial the target acquisition display was located where it was in manual trials (neutral condition), in another the display was re-located proximal to the system monitoring display (proximal condition), and in the third was re-located distal to the system monitoring task (distal condition, see Fig. 2). Manual trials were three minutes in length and contained six monitoring deviations (two per minute, 30 seconds apart) and three surface targets. The three automated trials were four minutes in length and contained eight monitoring deviations (two per minute, 30 seconds apart) and four surface targets. Thus, summed manual and summed automated trials were equated for total time-on-task, for the total number of monitoring deviations, and for the total number of targets as well as for specific type of deviations, types targets, and time of individual events. Manual and automated trials were alternated in order to emphasize the 'automation' of the target acquisition as well as to track possible transfer effects after automated trials. The recurrent manual trials also served to emphasize/reinforce the 'neutral' display format as this format was present four times as often as either of the automated display formats.

2.5. Experimental procedure

Pilots signed a consent form and received full instructions on the three individual sub-tasks. Practice sessions were provided for each of the three sub-tasks individually as well as for the overall multi-task environment. The automated target acquisition condition was explained to each pilot and practice was provided. The pilot then completed the seven experimental trials in which manual and automated trials were alternated. Order of presentation for automated trials was counterbalanced across subjects. Just prior to the end of each trial, subjects gave three oral SWAT responses.

3. Experimental results

3.1. Manual trials

Since all pilots received practice prior to the experimental procedure it was expected that performance in the four manual trails would be similar and thus provide a baseline for the 'standard' or manual operating conditions. However, repeated measures analyses indicated that monitoring response times (both means and variances) and target response times were significantly greater in the first manual trial compared to the following three manual trials which did not differ significantly ($F(3, 30) = 6.07, p < .05$, $F(3, 30) = 4.932, p < .05$, $F(3, 27) = 12.82, p < .05$, respectively). Furthermore, percentage of target acquisition response was significantly lower in the first manual trial ($F(3, 30) = 26.98$, $p < .01$). An inspection of the data also indicated that the number of missed monitoring deviations in the first manual trial far exceeded other manual trials. When analysis was conducted on the three remaining manual trials only, there were no significant differences in performance on any of the sub-tasks. We concluded that pilots had not yet acquired stable performance on the full task during the first manual trial and, thus, performance in manual trials was calculated by summing data across the final three manual trials.

3.2. Automated versus manual trials

Overall performance was compared between the summed manual conditions versus summed automation conditions using matched t-tests. Results indicated less tracking error (1.19 vs. 1.37 rmse, $t(10) = 3.277, p < .05$), shorter monitoring response times (3.68 vs. 4.61 s, $t(10) = 2.651$, $p < .05$), shorter target response times (29.83 vs. 36.62 s, $t(10) = 7.987, p < .01$), and larger percentage of target responses (90.82 vs. 82.94%, $t(10) = 3.017$, $p < .05$) during the automated compared with the manual trials.

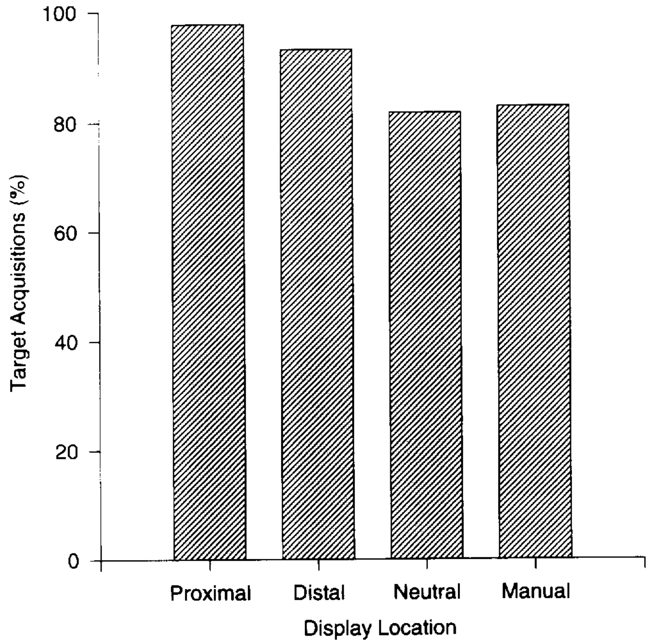

Fig. 3. Percentage of target task responses in automated and summed manual conditions. The figure indicates that pilots made more responses when the automated display was located distally or proximally to the system monitoring display than in the neutral or manual locations.

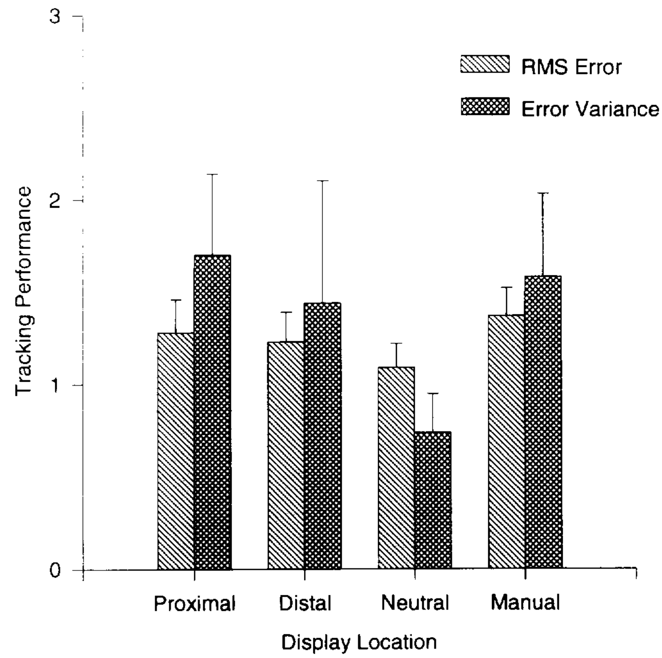

Fig. 4. Tracking error and tracking error variance in automated and manual conditions. The figure indicates that the neutral display condition was associated with reduced error and more consistent performance when compared to the proximal and manual conditions.

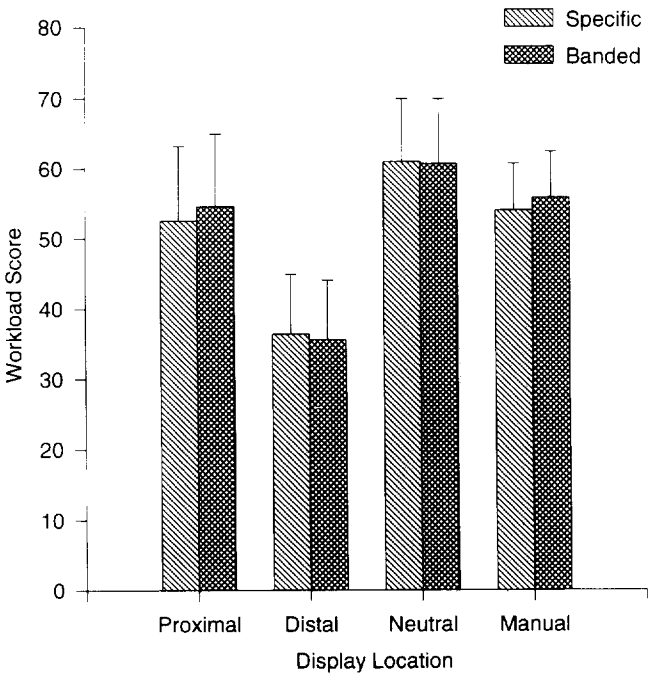

Fig. 5. SWAT banded and specific workload scores by automated trial. For both the banded and specific analyses, the data indicated that pilots reported significantly less workload for the distal display condition as compared to all other conditions.

3.3. *Automated trials*

The effect of the principal manipulation of this study (automated display location) was assessed by analyzing performance during the three automated trials. Performance for the summed manual trials was also included in the analysis as a baseline. The four total conditions were compared via matched *t*-tests as this procedure allowed the inclusion of the summed manual condition without violating assumptions of repeated measures. Results for target acquisition performance indicated an increased percentage of target responses for the proximal and distal conditions which both differed significantly from the neutral and manual conditions (see Fig. 3). For both tracking error and tracking error variance, the proximal condition differed from the neutral condition which itself differed from the manual condition (see Fig. 4).

	Neutral Position	Proximal Position	Distal Position
Tracking	↑	—	—
Monitoring	—	—	—
Target Acquisition	—	↑	↑
Workload	—	—	↓

Fig. 6. Summary of experimental findings. An up arrow indicates better performance, a horizontal line indicates no change in performance, and the down arrow indicates a reduction in workload. Note that the distal position is the only position associated with performance and workload benefits.

3.4. *Workload responses*

Banded and specific workload scores were calculated for the 11 pilots. The three automated conditions and the summed manual conditions were compared via matched *t*-tests. For both banded and specific workload scores the distal condition differed significantly from all other conditions, which did not differ between themselves (see Fig. 5). A summary of experimental results is presented in Fig. 6.

4. Discussion

4.1. *The benefit of automation*

The comparison of manual and automated trials clearly shows the benefit of target acquisition automation. There is less tracking error, shorter monitoring response times, shorter target response times, and a larger percentage of target responses in automated compared with manual trials. Importantly, performance on all tasks improved during automation, demonstrating that automation benefits are both local (within the task being automated) and global (affecting all other tasks in the set). The benefits for automated target acquisition are not surprising. During automation the automated targeting system scans for and identifies a target, considerably reducing the need for the pilot to continuously search the surface below them. However, the pilot's role in this task during automation was only reduced, not eliminated. As soon as a target was 'located' by the automatic system, the display began to 'cycle' between each of the three potential target types, providing a salient visual cue that a target was approaching. At this point the pilot still had to search the surface and locate the target to confirm that the weapon selected by the system was indeed correct. The observed advantage then is not simply the result of load-shedding in which two tasks can, for example, be performed better than three [31]. The target acquisition task, while nominally reduced in demand, was still formidable as targets were very difficult to see and an overt emphasis in training was placed on response accuracy. Consequently, while automation benefits for the target acquisition were not unexpected, the results are informative. The superiority of automated trials then confirms the value of automation and re-enforces our earlier findings and those of others that selective automation is helpful (e.g. [18,22,32–34]).

Moreover, benefits associated with the employment of an automation strategy in which control of specific tasks can alternately come under manual or automated control is consistent with the proposed goals of adaptive allocation [35,14].

4.2. Functional grouping of displays

Results for performance and workload for the three automated display locations provide insight into the relevance of the PCP in the context of adaptive automation in multi-task systems. We interpret performance and workload in the three automated trials within a limited resource framework [31,36]. Basically, a finite amount of attentional resources are devoted to the manual performance of the three tasks. Automation serves to free up a portion of these resources which can either make the overall task easier or permit improvements to component sub-tasks. We assume that the same amount of resources are freed-up in each of the automated conditions. According to the PCP approach we expected the proximal display location to be related to superior performance and a reduced workload when compared to performance for the distal and neutral display locations.

At first glance there appears to be little support for PCP, since the display position during automation did not stand out with respect to performance or workload. Workload data indicated that the neutral and proximal layouts were associated with approximately the same level of workload as manual conditions, indicating that freed resources weren't absorbed but instead allocated elsewhere. In the neutral layout condition these resources were devoted to the tracking task, resulting in better and more consistent tracking performance. Given that the layout was the same as in the manual condition, this effect can be regarded as a pure form of the automation benefit. That the resources were allocated to tracking was not surprising given that the tracking task presents continuous demand coupled with the tendency of pilots to treat 'flying the aircraft' as the primary task [19]. However, the same resources freed-up in the proximal layout condition were not allocated to tracking but were localized to the target acquisition task, resulting in a larger percentage of acquired targets. This would appear to support the PCP but performance did not differ between proximal and distal layouts as expected, and this observation is inconsistent with the derived prediction. There two explanations we think are relevant. First, the PCP is not relevant to the layout of displays in an adaptively automating system. Effects demonstrated in this experiment were largely due to a pure benefit of automation. Further, a simple relocation of tasks stimulated alternative strategies by pilots, sometimes resulting in better performance on component tasks, other times resulting in reduced workload.

However, we feel the demonstrated effects can indeed be accounted for within the PCP framework. Wickens and Carswell [8] defined two dimensions of proximity or similarity: perceptual proximity and processing proximity. Perceptual proximity dictates that two displays conveying similar information should be close together. We assumed here the automated task is transformed to a monitoring task and thus should be located close to the other monitoring task to achieve functional proximity. However, the automated target acquisition task still requires action by the pilot. To complete the task during automation (to identify and destroy the target) there are really two sources of information: the automated display and the surface target. The two information sources are used as part of the same task and thus define a separate dimension–processing or mental proximity. PCP postulates that if there is close processing proximity, then close perceptual proximity is required. The implications in our experiment are ironic. Our physical distal condition should have been more accurately labeled the 'proximal' condition because it placed the two sources of information required for the automated target acquisition task in close proximity (see Fig. 2). Given this form of grouping, data now support PCP as it was this condition that was associated with increased performance on a component task, but with significantly reduced workload. In effect, the distal (now proximal) display layout was the only layout which produced *both* performance and workload benefits.

4.3. Summary and implications for display layout design

Performance and workload data therefore appear to support the proximity compatibility principle. The creation of a proximal display layout resulted in superior performance and a significant reduction in workload. However, these data should be viewed as partial support for the PCP. The two dimensions of the principle discussed here represent only a small part of a much larger taxonomy including principles for integrative and non-integrative processing. We should also note that our manipulations involved only spatial proximity, while there are also changes that can be effected to the physical rendering of two or more displayed information sources in order to create psychological closeness between them. These techniques may include adding line segments connecting or enclosing displays, using color, orienting displays along the same axis, showing each source in decorative perspective, or using the same analog property (e.g., length, orientation, or brightness [8].

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