Prospective Memory Failures in Aviation: Effects of Cue Salience, Workload, and Individual Differences

Kathleen D. Van Benthem; Chris M. Herdman; Rani G. Tolton; Jo-Anne LeFevre

INTRODUCTION: Prospective memory allows people to complete intended tasks in the future. Prospective memory failures, such as pilots forgetting to inform pattern traffic of their locations, can have fatal consequences. The present research examined the impact of system factors (memory cue salience and workload) and individual differences (pilot age, cognitive health, and expertise) on prospective memory for communication tasks in the cockpit.

METHODS: Pilots ($N = 101$) flew a Cessna 172 simulator at a non-towered aerodrome while maintaining communication with traffic and attending to flight parameters. Memory cue salience (the prominence of cues that signal an intended action) and workload were manipulated. Prospective memory was measured as radio call completion rates.

RESULTS: Pilots' prospective memory was adversely affected by low-salience cues and high workload. An interaction of cue salience, pilots' age, and cognitive health reflected the effects of system and individual difference factors on prospective memory failures. For example, younger pilots with low levels of cognitive health completed 78% of the radio calls associated with low-salience memory cues, whereas older pilots with low cognitive health scores completed just 61% of similar radio calls.

DISCUSSION: Our findings suggest that technologies designed to signal intended future tasks should target those tasks with inherently low-salience memory cues. In addition, increasing the salience of memory cues is most likely to benefit pilots with lower levels of cognitive health in high-workload conditions.

KEYWORDS: ageing, pilot, cognitive health, working memory.

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Prospective memory enables people to complete intended tasks in the future. In aviation, pilots' prospective memory failures, such as forgetting to inform other aircraft of their location or not setting flaps prior to takeoff, can result in serious accidents and loss of life.[4–7] Stakeholders in aviation safety have recently called for studies examining predictors of prospective memory, and, in particular, research paradigms that investigate individual differences in prospective memory performance.[6] Investigating determinants of prospective memory for complex occupations, such as those found in aviation, requires a multipronged approach that explores system factors and individual pilot differences. The present research examined whether system factors, such as the features of memory cues that pilots rely upon to signal intended tasks, and workload levels (manipulated by terrain difficulty and traffic volume) were associated with prospective memory failures. We also examined whether individual pilot differences, such as age, cognitive health, or level of expertise, were associated with errors in prospective memory.

To date, researchers have not used experimental methods to directly investigate effects of system factors and individual differences on the prospective memory of pilots. However, numerous studies have found that age, expertise, and cognitive health (often indexed by working memory and processing speed) were associated with other cognitive aspects of pilot performance.[14,28,29] For example, older age, lower levels of working

From the Institute of Cognitive Science and the Visualization and Simulation Centre, Carleton University, Ottawa, Ontario, Canada; and Occupational and Aviation Medicine, University of Otago, Newtown, Wellington South, New Zealand.

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Address correspondence to: Kathleen D. Van Benthem, M.H.S., Institute of Cognitive Science, Carleton University, 1125 Colonel By Drive, Ottawa, Ontario K1S 0A3, Canada; kathy_vanbenthem@carleton.ca.

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memory, and operator expertise were associated with diminished accuracy in executing air traffic control instructions.[28,29] Coffey et al.[2] found that older age was associated with less detection of critical events that occurred both inside and outside the cockpit. Morrow et al.[19] found that older and less experienced pilots had lower read back accuracy for air traffic control information and poorer recall of information from aviation charts. These studies show that individual differences in pilot age, cognitive health, and expertise are associated with cognitive tasks in the cockpit,[13] suggesting that these factors might also influence pilots' prospective memory.

Uttl[33] described three types of prospective memory tasks. Holding an intention in memory over a period of time is called prospective memory proper. For example, remembering to file a flight plan uses prospective memory proper. Memory for vigilance relies upon maintaining an intention in consciousness while engaged in other tasks. Vigilance events usually take place over shorter time periods. The requirement to check altitude at regular intervals could be described as vigilance prospective memory. The third type, habitual prospective memory, is similar to the proper form, except that the tasks are performed routinely, such as remembering to complete radio calls at regular locations in a pattern. There are also two types of memory cues that signal the appropriately timed execution of an intended act. Memory cues can be time-based, such as when a task should be performed at a specific future time (e.g., three o' clock). Memory cues can also be event-based, such that the execution of the task is associated with some future event (e.g., on approach). Dismukes[4] found that pilots performed all three types of prospective memory tasks. However, habitual tasks associated with event-based memory cues were particularly common and were linked with prospective memory failures.

In an analysis of Aviation Safety Reporting System reports, 74 of the 75 incidents that identified a memory failure involved prospective memory errors.[24] These prospective memory failures were categorized as: 1) errors in monitoring for the correct occasion to initiate the task; 2) inadequate cues available to initiate the activity; 3) the tendency to perform habitual or routine tasks in place of the intended task; and 4) poorly formed intentions to perform the task. Prospective memory failures were also identified in a field study where Dismukes and Berman[5] placed an observer in the jump seat of cockpits during 60 airline flights to collect data regarding interruptions, errors in checklist execution, and monitoring of cockpit information displays. Deviations from standard operating procedures were a common precursor to prospective memory failures. Even experienced pilots sometime failed to complete routine tasks. Such findings indicate that system factors such as inadequate memory cues, interruptions, and deviations from standard operating procedure were associated with prospective memory failures and were potential sources of risk in aviation.

Other system factors relevant to the investigation of prospective memory in aviation concern features of the memory cues associated with task initiation. Memory cues have features that render them hypothetically more likely (high-salience) or less likely (low-salience) to act as signals for the prospective memory task.[3,12,15] For example, Cohen et al.[3] found that spatially displacing a letter cue (e.g., a ^{b} c) within a string of letters improved prospective memory. Although all letters were located within the field of view, the slight displacement of the letter cue appeared to increase its salience, as compared to conditions where the letter cue was not displaced. Thus, greater salience or prominence of the cue was associated with better prospective remembering. Another system factor that might influence prospective memory in aviation involves the features of the situation. Nowinski and Dismukes[23] found that prospective memory was better when the situational context of the task at retrieval was similar to the context at initial processing, where the memory cue was first encoded. This effect, named associative activation by Nowinski and Dismukes, is similar to the encoding specificity principle first described by Tulving and Thomson[32] in studies of retrospective memory. Memory cues for word recall were most effective when features of the cues matched features originally encoded at the time of stimulus input. Workload is a third system factor pertaining to context that could have implications for prospective memory in aviation settings. Stone et al.[27] found that workload affected prospective memory in an air traffic control task, such that more failures were found in high- than in low-traffic volume conditions. In summary, system factors such as the salience of memory cues, the features of the task context, and workload may be relevant factors for understanding pilots' prospective memory performance.

The context where prospective remembering takes place has also been associated with individual difference factors such as age and cognitive health. Of particular interest for the present research is the age paradox. The age paradox refers to the observation that older and younger adults perform similarly in studies where the prospective remembering takes place in naturalistic environments (e.g., at the participants' home),[16,17] whereas in laboratory-based settings younger adults generally outperform older adults on a variety of prospective memory tasks. This pattern suggests that prospective memory could be one cognitive function that is spared the typical effects of older age when the task affordances found in natural contexts are available.[9–11] However, Uttl's meta-analysis of age and prospective memory found that older adults performed as well as younger adults primarily for prospective memory proper tasks that were associated with time-based memory cues in naturalistic settings.[33] Habitual tasks with event-based cues in naturalistic settings showed a different pattern of results, where older age was associated with poorer prospective memory performance. This latter finding is relevant for aviation where routine flight involves carrying out numerous habitual tasks associated with event-based cues. For example, when a radio transmission interrupts a pilot just before lowering the flaps on final approach, the intention to adjust the flaps must be maintained in the mind of the pilot and then executed at an appropriate point in the future. To date, however, no published experimental studies have incorporated the naturalistic environment necessary for a comprehensive investigation of individual differences and prospective memory for piloting tasks. Moreover, the effects of individual differences on habitual prospective memory tasks associated with event-based cues are unknown in the aviation domain.

The present research measured radio call completion rates, a common habitual prospective memory task in aviation. Pilots flew low- and high-workload missions in a Cessna flight simulator (Flight Training Device Level 6). The simulation environment (including simulated traffic communication) was used to present a natural and familiar general aviation setting in which pilots flew consecutive patterns at a non-towered aerodrome. The presentation, by headset, of typical radio chatter and the requirement that pilots provide spoken radio calls as normally delivered at non-towered aerodromes contributed to the naturalistic features of our flight simulation protocol.

System factors and individual differences were hypothesized to affect pilots' prospective memory. In terms of system factors, it was expected that performance would be influenced by the salience of memory cues and by workload. Specifically, we hypothesized that pilots would be less likely to complete radio calls associated with low-salience memory cues than radio calls associated with high-salience memory cues. It was also expected that more failures to complete radio calls would be found in the high- than the low-workload condition. The effects of workload and memory cue salience were expected to interact because under high-workload conditions, less working memory resources would be available to detect and process low-salience cues.

An effect of age was predicted where radio call completion rates were expected to be lower for older than for younger pilots. This prediction was made despite the use of a naturalistic setting because of the habitual and event-cued nature of our prospective memory task.[17] Similarly, pilots with low levels of cognitive health were expected to complete fewer radio calls than pilots with high levels of cognitive health. In contrast, performance was expected to be similar across levels of pilot expertise due to the routine aspect of radio call tasks during standard pattern flight. Interactions between system and individual difference factors were examined to gain a comprehensive understanding of prospective memory failures in aviation.

METHODS

Pilots were recruited from local flying clubs and schools. Inclusion criteria involved having a minimum of a valid student pilot permit and a valid medical certification to fly, as well as being 18 yr of age or older. This study was approved by the university ethics committee operating under the Canadian Tri-Council Code of Ethics for psychological research. Pilots provided written informed consent after a description of the study purpose and activities.

Subjects

Pilots ($N = 101$) represented a range of pilot rating and expertise, including student ($N = 16$), recreation/private (visual flight rules, no additional rating; $N = 41$), private (instrument flight rules or visual flight rule with additional private pilot rating; $N = 24$), and military, commercial, or airline transport pilots ($N = 20$). Pilots were grouped as either younger (age 19 to 50) or older (age 51 to 81). The younger group averaged 36.3 yr of age ($N = 65$, SD = 10.1) and the older group averaged 61.3 yr ($N = 35$, SD = 7.6 yr). Regarding flight experience, the means and ranges for each age group were as follows: the younger pilots had been licensed for 7.5 (1−33) yr and had 504.4 (5−8000) total flying hours, of which 34.8 (0−308) h were flown as pilot-in-command in the past 12 mo. The older pilots had been licensed for 24.7 (1−63) yr and had 893.4 (34−5440) total flying hours, of which 27.2 (0−150) h were flown as pilot-in-command in the past 12 mo. In keeping with Taylor et al.,[13,28,30] pilots were divided into expertise groups based upon pilot rating, with students and recreation/private (no additional rating) in the low-expertise category, whereas private pilots with advanced ratings and air transport, commercial, or military pilots comprising the high-expertise group.

Confounds between pilot age and experience are difficult to overcome. Although older age tends to be associated with poorer performance on cognitive tasks and flight summary scores,[28–30] progression through the lifespan is also associated with a rich repertoire of past experience and training.[20] A one-way ANOVA was conducted to examine how pilot age, as a continuous variable, varied among the four pilot rating groups. Older age showed a marginal association with higher pilot rating [$F(3,97) = 2.26$, $P = 0.087$]. To examine in more detail how age was associated with pilot expertise, secondary one-way ANOVAs were conducted with pilot age as the independent variable and years licensed and total and recent hours flown as the criterion variables. As would be expected, older age was associated with more years licensed ($P < 0.001$). There were, however, no significant relationships between pilot age and recent pilot-in-command hours or total hours flown ($P > 0.1$). Because older pilots in this sample tended to have higher levels of expertise than younger pilots (as per rating and hours flown), any potential deleterious effect of age on prospective memory would occur in spite of the older pilots having slightly higher levels of expertise.

Equipment

The flight simulator was a Cessna 172 aircraft cockpit and fuselage running Microsoft Flight Simulator X™ software. The simulator was equipped with Cessna 172 flight controls and physical instruments. Large screens provided 45 degrees of vertical field of view and 120 degrees of horizontal field of view. Pilots monitored radio communication from other simulated aircraft at their airfield and heard low-level chatter from a larger distant airport. A data acquisition computer recorded simulated flight parameters such as aircraft heading, altitude, and airspeed. Relevant verbal responses by pilots, such as radio calls completed, were recorded by the experimenter.

Procedure

Pilots were scheduled for a morning or afternoon session according to their convenience. A questionnaire regarding flying experience and a cognitive health screen, the DCAT^{TM}, [8] were completed during the same portion of the day as the simulated flight. A visual and verbal presentation outlining the requirements for flying a "perfect pattern" followed by a practice session (four full patterns with experimenter feedback) were provided to familiarize pilots with the flight simulation environment, the aircraft controls, and the communication tasks. After the practice session, pilots flew six left hand patterns, three at an airfield representing the low-workload condition and three at an airfield representing the high-workload condition. Detailed instructions regarding the radio communication tasks were provided in verbal, written, and graphic forms. Pilots provided feedback regarding the flight task via a five point Likert-type scale at the end of the session. This feedback showed that the pattern flying procedures followed in this study were either similar or very similar to pilots' own pattern procedures. Thus, despite being simulated flight, the tasks and procedures were considered familiar.

In laboratory studies of prospective memory, participants are often instructed to perform some act upon the recognition of a predefined memory cue. In contrast, in naturalistic tasks that require habitual-type remembering, such as communicating positions in a pattern, there are typically no explicit instructions regarding memory cues. A mental intent to perform an act is formed and maintained (most likely by repeated practice of the same procedures) and strategies and cues for remembering will vary with the experience and preferences of the individual. We replicated this naturalistic prospective remembering by instructing pilots to complete radio calls at six different locations as part of their instructions on how to fly the "perfect pattern". Other instructions included the specific altitude, heading, and airspeed for each leg of the pattern, as well as details of the simulator flight controls and important features of the two aerodromes where the flights took place. The radio call instructions were not singled out as any more or less important than the rest of the pattern instructions. Importantly, pilots were instructed to fly as they normally would while also adhering to the parameters provided by the experimenter. The experimenter did not provide suggestions for memory cues, nor was the term "prospective memory" used by the experimenter.

Pilots were provided with detailed instructions regarding the six radio calls they were to remember to perform during each pattern they completed. As per standard procedures, the pilots' radio calls were to convey information pertaining to their identification and current position in the pattern. As shown in **Fig. 1**, six radio calls were required for each pattern. The first call was for initial rolling on runway (one), or for subsequent runway touch-and-go or runway overshoot events. The remaining calls were for airborne (two), turning downwind (three), mid-downwind (four), turning base (five), and turning final (six). The radio calls we deemed to have low-salience memory cues were calls two and four. This is because airborne and mid-downwind calls had very limited visual cues (e.g., little change occurring with the horizon), and were not accompanied by physical cues (e.g., physically manipulating the control column). The two radio call positions deemed to have high-salience memory cues were the calls for turning downwind (three) and turning base (five). These high-salience cues included visual cues where there were clear changes occurring with the horizon and physical cues, where pilots were performing actions using aircraft controls. These pilot actions were also congruent with the information contained in the radio call. Turning base was considered the radio call with the highest-salience cues because of the physical acts resulting in turning and descending, and the visual changes to the horizon and approaching runway to the left. The high salience nature of these cues, afforded by the natural context of flight, was hypothesized to lead to higher rates of radio call completion as compared to low-salience memory cues. As such, the categorization of radio calls as having either low- or high-salience memory cues was achieved by exploiting the natural features inherent in each of the six different radio call locations.

The remaining two radio calls, one (runway) and six (final approach), were considered to have moderately salient cues and are not discussed in this analysis. Pilots received a point for each required call completed during flight, and were not penalized for providing extra calls (e.g., short final). Six calls per pattern for each of three patterns in each of two workload conditions allowed for a maximum of 36 total radio communication calls to be recorded. After removing (from statistical analyses only) the 12 radio calls (2 per pattern) not considered associated with low- or high-salience cues, there were 6 radio calls per each workload × salience condition. Scores were converted to percent completion rates for each workload and cue salience condition.

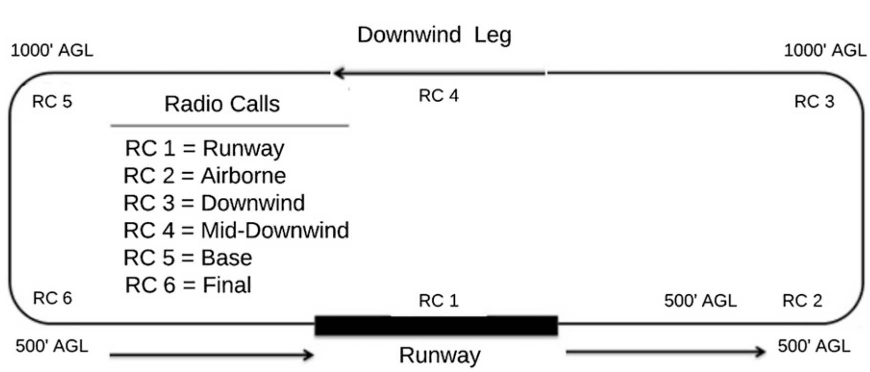

Fig. 1. Standard pattern with six radio call locations noted (RC 1−6). RC = radio call. AGL = above ground level.

Providing the same instructions and background context for all pilots during the encoding of the intent to remember to perform the radio call tasks provided an important control feature in the present study. Ensuring that the identical context was used for each pilot when encoding the intent to complete the radio calls controlled for associative activation,[23] a factor known to influence prospective memory performance. The cues available as signals for remembering to perform the radio tasks were considered to be implicit event-based cues because each radio call was to be completed at a specified location (e.g., turning downwind) or pattern event (e.g., immediately after takeoff). The experimenter did not provide explicit cues to assist in remembering, except during the practice session when verbal prompts were provided if a radio call was forgotten. Feedback regarding the completion of radio calls was given by the experimenter during the four practice patterns to ensure pilots were familiar with the expectations of the radio call task and could perform them accurately during practice.

Features of the flight environment were manipulated to create two workload conditions. In the low-workload condition, pilots flew at an aerodrome with flat terrain and no other aircraft during pattern one, one other aircraft during pattern two, and two other aircraft during pattern three. In the high-workload condition, the pilots flew in mountainous terrain with two other aircraft during pattern one, three other aircraft during pattern two, and four other aircraft during pattern three. In both workload conditions, pilots were required to maintain situational awareness of their own aircraft and other relevant aircraft. In each condition the simulated weather was clear and no unusual or critical events with respect to instrumentation or aircraft controls were introduced.

Cognitive health was measured using the DCAT™.[8] The DCAT™ is a computerized touch-screen cognitive health measure comprised of six individually scored subtests, each designed to capture elements of cognitive function implicit in the abilities required for safe driving. The DCAT™ reports only a 5% error rate in identifying older adults who might be at risk when operating a motor vehicle. Because this tool predicts risk for older adults in regard to the complex task of driving, the DCAT™ was selected as a potential predictor of performance for older aviators. To our knowledge, the current study is the first to use the DCAT™ in an aviation setting. The DCAT™ produces z-scores for each of the six subtests that reflect age-normed accuracy and timing of the responses, and a single score that represents driver safety (calculated by proprietary algorithms). Each pilot completed all six subtests. Subtests 2 and 6 were used in the current analysis because they incorporate information on monitoring and working memory abilities: the indices of cognitive health in the present study. The z-scores from subtests 2 and 6 were averaged, and low and high cognitive health groups were formed by median split.

The Span of Attentional Field test (Subtest 2) is a dual-task measure of attentional capacity. Pilots performed a lexical decision task (recognizing a target word from nontarget words presented briefly and individually in the center of the computer screen) while concurrently noting and then recalling the position of a small target dot in the periphery. This task was completed without and then with distractor stimuli in the periphery. Subtest 2 scores are based on speed and accuracy on both portions of the subtest and are age-normed.

In subtest 6, The Identification of Driving Situations, pilots watched 10 short narrated video clips of actual driving footage (approximately 5 to 15 s each) and then answered a question relating to some aspect of scene detail, spatial judgment, or driving safety. This measure required integration of the auditory and visual information. A second after the presentation of each video clip, a question was asked with four potential answers appearing on the screen (e.g., "how should you respond in this situation?" or "what is the most dangerous aspect of this scene?"). Less than 30 s were provided to read potential answers and tap the screen indicating a best response. This task is scored as the number of questions answered correctly out of 10 and is age-normed.

RESULTS

The mean radio call completion rates, in order from highest to lowest, were as follows: turning base (97.1%), turning downwind (92.9%), mid-downwind (79.2%), and airborne (73.4%). In keeping with the hypotheses, prospective memory performance was analyzed in a 2 (cue salience: high, low) × 2 (workload: low, high) × 2 (expertise: low, high) × 2 (age: younger, older) × 2 (cognitive health: low, high) mixed ANOVA, with repeated measures on cue salience and workload. All reported effects were significant at $P < 0.05$, unless otherwise noted. For interactions, 95% confidence intervals were used to compare across conditions. All predictor variables were divided into two levels (low and high) to maximize the power of the test for a five-factorial ANOVA with 101 observations, moderate effect sizes, and alpha set at 0.05.

Prospective memory performance varied with cue salience and workload, as hypothesized. Pilots completed more radio calls in the high- than in the low-salience memory cue condition [95.3% vs. 75.6%; $F(1,93) = 103.23$, MSE = 324.84, $\eta_p^2 = 0.53$]. Pilots also completed more calls in the low- than in the high-workload condition [88.7% vs. 82.2%; $F(1,93) = 11.74$, MSE = 309.36, $\eta_p^2 = 0.11$]. Cue salience and workload interacted, as shown in **Fig. 2** [$F(1,93) = 5.96$, MSE = 198.06, $\eta_p^2 = 0.06$]. The effect of workload was smaller in the high-salience cue condition than in the low-salience cue condition. This pattern suggests that high-salience cues are generally effective regardless of workload. In contrast, low-salience cues are less effective, especially when the workload is high.

With respect to individual differences, younger pilots completed more radio calls than older pilots [89.1% vs. 82.3%; $F(1, 93) = 4.45$, MSE = 136.5, $\eta_p^2 = 0.05$] and age interacted with cue salience [$F(1,93) = 9.06$, MSE = 324.8, $\eta_p^2 = 0.09$]. Older and younger pilots completed a similar percentage of calls with high-salience cues. However, in the low-salience cue condition,

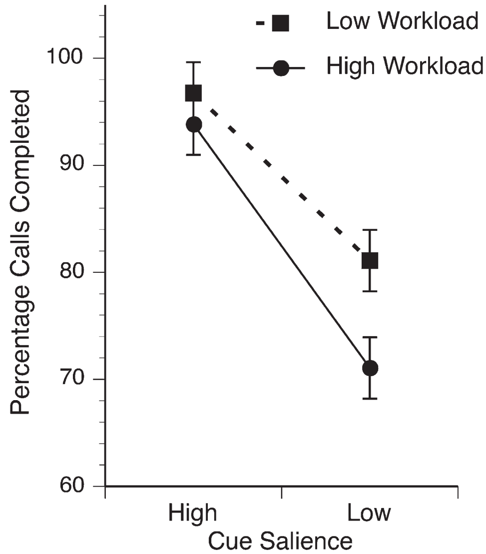

Fig. 2. Interaction of workload and cue salience. Bars represent 95% confidence intervals.

older pilots completed fewer calls than younger pilots. Workload and age did not interact (i.e., the effect of high workload was similar for younger and the older pilots).

Prospective memory performance varied significantly with cognitive health. Pilots with lower cognitive health scores completed 81.4% and pilots with age-appropriate cognitive health scores completed 89.5% of the radio calls [$F(1, 93) = 10.2$, MSE = 136.5, $P = 0.002$, $\eta_p^2 = 0.10$]. Furthermore, the influence of cognitive health on performance varied with cue salience [$F(1, 93) = 3.88$, MSE = 324.8, $P = 0.052$, $\eta_p^2 = 0.04$]. All pilots showed effects of cue salience, but those with low cognitive health were more affected by low-salience memory cues.

The three-way interaction of age, cue salience, and cognitive health approached significance and illustrates which pilots were most affected by cue salience and cognitive health [$F(1, 93) = 2.84$, $P = 0.095$, MSE = 324.87, $\eta_p^2 = 0.03$]. As shown in **Fig. 3**, regardless of cognitive health group or age, pilots tended to remember to complete the radio calls with high-salience cues.

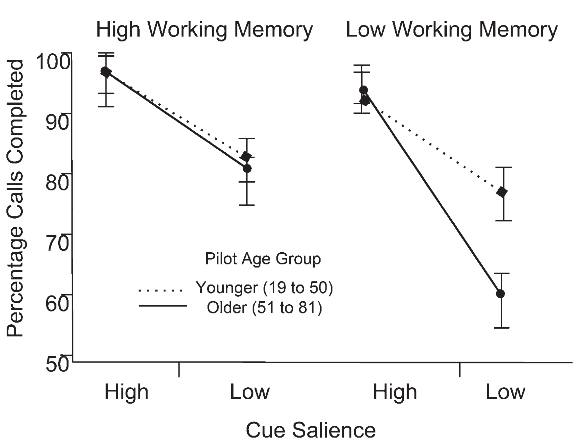

Fig. 3. Interaction of cue salience, cognitive health, and age. Bars represent 95% confidence intervals.

In contrast, in the low-salience condition, older pilots with low cognitive health failed to complete a substantial number of radio calls when compared to younger pilots with low cognitive health.

Pilots with lower expertise tended to complete fewer radio calls than pilots with higher expertise [83.1% vs. 87.8%; $F(1,93) = 3.57$, $P = 0.062$, MSE = 136.4, $\eta_p^2 = 0.04$]. The effect of expertise on prospective memory did not interact significantly with age, cue salience, workload, or cognitive health ($F < 1$). Thus, higher expertise did not reduce the negative effects of older age on radio call completion rates.

Two multiple regression analyses were done to determine if dichotomizing expertise and age into low and high categories reduced the predictive power of these variables. In the first regression, the dependent variable was the percentage of radio calls completed for high-salience memory cues. Predictors were entered in three blocks. The first block of predictors indexed pilot expertise, specifically rating level (ordinal, four-levels), recent pilot-in-command hours (continuous), and total hours flown (continuous). The second block indexed cognitive health (the average of DCAT™ subtests 2 and 6). The third block represented pilot age (continuous). In the model with all three predictor blocks, pilot cognitive health was the only significant predictor of performance in the high-salience cue condition [$\beta = 0.34$, $t = 3.41$, $P = 0.001$]. The full model accounted for 16.2% of the variance in prospective memory scores in the high-salience cue condition.

The second multiple regression analysis included the same expertise, cognitive health, and age variables, but predicted the low-salience cue radio calls. In the final model, age and cognitive health were significant predictors of radio call performance in the low-salience cue condition [$\beta = -0.23$, $t = -2.28$, $P = 0.025$, and $\beta = 0.28$, $t = 2.93$, $P = 0.004$, respectively]. The full model accounted for 20.4% of the variance in prospective memory scores associated with low-salience cues. None of the pilot expertise variables contributed significantly to the model.

DISCUSSION

The present research investigated whether system factors, such as the salience of the memory cues that signal pilots to perform the intended task and workload levels, were associated with prospective memory failures. We also examined whether individual differences in pilot age, cognitive health, and level of expertise were related to prospective memory errors. Prospective memory was measured in terms of radio call completion rates.

As expected, pilots' prospective memory performance was related to the salience of the radio call memory cues, the workload of the flight environment, age, and cognitive health. All pilots performed well on the prospective memory task when high-salience memory cues were available. High-salience cues consisted of visual changes to the horizon, as well as internal indicators such as sensations associated with turning and manipulation of the controls. In contrast, prospective memory performance was reduced when the memory cues were not salient among the ongoing activities. The present findings also showed that a high-workload environment was associated with significantly poorer prospective memory performance for all pilots. The effect of workload in this study supports observations in aviation[7] indicating that high workload poses a risk to prospective memory performance. Furthermore, there was an interaction between cue salience and workload wherein a significant drop in radio call completion rates was observed in the low-salience, high-workload condition.

Examination of the interaction between system and pilot factors allows a more comprehensive understanding of the factors that influence pilots' prospective memory. Lower prospective memory performance was found for older pilots, and for pilots with lower levels of cognitive health. The effects of pilot age and cognitive health were strongly tied to memory cue salience. When cue salience was low, older pilots with lower levels of cognitive health showed especially poor performance.

In our sample, expertise did not mitigate the effects of ageing and cognitive health on prospective memory performance. In various occupational domains, expertise has been posited to "protect" skills that might otherwise deteriorate due to age or cognitive decline (see Salthouse[25] for a review).[26] Similarly, expertise has been examined as a moderator of age effects on pilot performance.[14,18] In the present research, pilots with high expertise showed a slight trend toward higher radio call completion rates than low-expertise pilots, but this effect was not statistically significant. Pilot expertise also did not interact significantly with age to predict performance as researchers have suggested it might.[18–20] Findings in the field of aviation have been mixed with respect to expertise interacting with age in communication tasks. Morrow[19,20] noted a beneficial effect of increased total flight hours for older pilots for air traffic control tasks. On the other hand, Taylor et al.[29] found that higher pilot rating did not attenuate age effects for air traffic control communication tasks. The general finding that prospective memory errors have been reported for pilots with varying expertise, despite the use of checklists,[5] suggests that in aviation, other factors might override the influence of expertise on prospective memory performance.

The present research found that memory cue salience was a key system factor affecting pilots' prospective memory for communication tasks. Older pilots had more prospective memory failures than younger pilots, particularly when the environment did not strongly signal the memory task (i.e., memory cues were low in salience). Thus, measures to augment the salience of cues might be important in maintaining prospective memory performance across the lifespan. Similarly, system support tools have been found to attenuate age differences observed for other pilot communication tasks. For example, simple measures, such as note-taking, reduced the effect of age on pilot read-back accuracy for air traffic control messages.[21,22] Augmenting the salience of prospective memory cues could benefit all pilots, but may be most beneficial for older pilots or those with lower cognitive health.

The effects of cognitive health shown in the present study speak to the importance of cognitive health screening in addressing risk for prospective memory failures for pilots of any age. The present study used age-normed measures of cognitive health that primarily indexed working memory ability. Pilots of any age might be vulnerable to declines in working memory that are related to illness, side-effects from medication, fatigue, or an event such as a concussion. For example, Transport Canada recommends that pilots with multiple sclerosis be assessed every 6 mo to monitor their physical and neuropsychological health.[31] Presumably this is recommended because even individuals with mild and recently diagnosed early relapsing-remitting multiple sclerosis have shown declines in working memory when compared to control subjects.[1] In sum, the risk of prospective memory failures could be heightened when cognitive health has been compromised.

The present research showed that both system factors and individual differences influenced pilots' prospective memory for habitual tasks associated with event-based memory cues. Our findings imply that technologies designed to signal intended future tasks should target those tasks with inherently low-salience memory cues. The greatest benefit of increasing the salience of memory cues might be found in high-workload conditions and for older pilots with lower levels of cognitive health.

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Authors and affiliations: Kathleen D. Van Benthem, M.H.S., and Jo-Anne LeFevre, Ph.D., Institute of Cognitive Science, and Chris M. Herdman, Ph.D., Visualization and Simulation Centre, Carleton University, Ottawa, Ontario, Canada, and Rani G. Tolton, M.D., Occupational and Aviation Medicine, University of Otago, Newtown, Wellington South, New Zealand.

REFERENCES

1. Berrigan LI, LeFevre JA, Rees LM, Berard J, Freedman MS, Walker LA. Cognition in early relapsing-remitting multiple sclerosis: consequences may be relative to working memory. J Int Neuropsychol Soc. 2013; 19(8):938–949.
2. Coffey E, Herdman CM, Brown M, Wade J. Age-related changes in detecting unexpected air traffic and instrument malfunctions. Proceedings of the 14th International Symposium on Aviation Psychology; 2007 April 23-26; Dayton, OH. Dayton (OH): Wright State University; 2007.
3. Cohen A-L, Dixon RA, Lindsay DS, Masson ME. The effect of perceptual distinctiveness on the prospective and retrospective components of prospective memory in young and old adults. Can J Exp Psychol. 2003; 57(4): 274–289.
4. Dismukes RK. Prospective memory in aviation and everyday settings. Prospective memory: Cognitive, neuroscience, developmental, and applied perspectives. In: Kliegel M, McDaniel MA, Einstein GO, editors. Prospective memory: cognitive, neuroscience, developmental, and applied perspectives. New York: Lawrence Erlbaum Associates; 2008:415–435.

5. Dismukes RK, Berman B. Checklists and monitoring in the cockpit: why crucial defenses sometimes fail. Moffett Field (CA): National Aeronautics and Space Administration, Ames Research Center; 2010. Technical Memorandum NASA/TM-2010-216396.
6. Dismukes RK, Loukopoulos LD, Barshi I. The multitasking myth: handling complexity in real-world operations. Farnham, Surrey (UK): Ashgate Publishing, Ltd.; 2012.
7. Dismukes RK, Nowinski J. Prospective memory, concurrent task management, and pilot error. In: Kramer A, Wiegmann D, Kirlik A, editors. Attention: from theory to practice. Oxford (UK): Oxford University Press; 2007.
8. DriveABLE Testing Ltd. Evaluations for at-risk experienced drivers. Edmonton, Alberta (Canada): DriveABLE Testing Ltd.; 1997.
9. Einstein GO, McDaniel MA. Normal ageing and prospective memory. J Exp Psychol Learn mem Cogn. 1990; 16(4):717–726.
10. McDaniel MA, Einstein GO, Stout AC, Morgan Z. Ageing and maintaining intentions over delays: do it or lose it. Psychol Aging. 2003; 18(4):823–835.
11. Hering A, Cortez SA, Kliegel M, Altgassen M. Revisiting the age-prospective memory-paradox: the role of planning and task experience. Eur J Ageing. 2014; 11(1):99–106.
12. Hicks JL, Cook GI, Marsh RL. Detecting event-based prospective memory cues occurring within and outside the focus of attention. Am J Psychol. 2005; 118(1):1–11.
13. Kennedy Q, Taylor J, Heraldez D, Noda A, Lazzeroni L, Yesavage J. Intraindividual variability in basic reaction time predicts middle-aged and older pilots' flight simulator performance. J Gerontol B Psychol Sci Soc Sci. 2013; 68(4):487–494.
14. Kennedy Q, Taylor JL, Reade G, Yesavage JA. Age and expertise effects in aviation decision making and flight control in a flight simulator. Aviat Space Environ Med. 2010; 81(5):489–497.
15. Kliegel M, Jäger T, Phillips LH. Adult age differences in event-based prospective memory: a meta-analysis on the role of focal versus nonfocal cues. Psychol Aging. 2008; 23(1):203–208.
16. Kvavilashvili L, Cockburn J, Kornbrot DE. Prospective memory and ageing paradox with event-based tasks: A study of young, young-old, and old-old participants. Q J Exp Psychol (Hove). 2013; 66(5):864–875.
17. Logie R, Maylor E, Della Sala S, Smith G. Working memory in event-and time-based prospective memory tasks: effects of secondary demand and age. Eur J Cogn Psychol. 2004; 16(3):441–456.
18. Morrow DG, Menard WE, Stine-Morrow EAL, Teller T, Bryant D. The influence of expertise and task factors on age differences in pilot communication. Psychol Aging. 2001; 16(1):31–46.
19. Morrow DG, Menard WE, Ridolfo H, Stine-Morrow EAL, Teller T, Bryant D. Expertise, cognitive ability, and age effects on pilot communication. Int J Aviat Psychol. 2003; 13(4):345–371.
20. Morrow DG, Miller LM, Ridolfo HE, Magnor C, Fischer UM, et al. Expertise and age differences in pilot decision making. Neuropsychol Dev Cogn B Aging Neuropsychol Cogn. 2009; 16(1):33–55.
21. Morrow DG, Ridolfo HE, Menard WE, Sanborn A, Stine-Morrow EAL, et al. Environmental support promotes expertise-based mitigation of age differences on pilot communication tasks. Psychol Aging. 2003; 18(2):268–284.
22. Morrow DG, Menard WE, Stine-Morrow EAL. Expertise and ageing in pilot communication: the role of environmental support. Proceedings of the Human Factors and Ergonomics Society 1999; 43(2):113–117.
23. Nowinski JL, Dismukes K. Effects of ongoing task context and target typicality on prospective memory performance: the importance of associative cueing. Memory. 2005; 13(6):649–657.
24. Nowinski JL, Holbrook JB, Dismukes RK. Human memory and cockpit operations: an ASRS study. In: Proceedings of the 12th International Symposium on Aviation Psychology; 2003 April 14-17; Dayton, OH. Dayton (OH): Wright State University; 2003.
25. Salthouse TA. Cognitive competence and expertise in ageing. In: Birren JE, Dvhsir KW, editors. Handbook of the psychology of ageing. San Diego (CA): Academic Press; 1990:301–310.
26. Sanjram PK, Khan A. Attention, polychronicity, and expertise in prospective memory performance: programmers' vulnerability to habit intrusion error in multitasking. Int J Hum Comput Stud. 2011; 69(6):428–439.
27. Stone M, Dismukes K, Remington R. Prospective memory in dynamic environments: effects of load, delay, and phonological rehearsal. Memory. 2001; 9(3):165–176.
28. Taylor JL, Kennedy Q, Noda A, Yesavage JA. Pilot age and expertise predict flight simulator performance - A 3-year longitudinal study. Neurology. 2007; 68(9):648–654.
29. Taylor JL, O'Hara R, Mumenthaler MS, Rosen AC, Yesavage JA. Cognitive ability, expertise, and age differences in following air-traffic control instructions. Psychol Aging. 2005; 20(1):117–133.
30. Taylor JL, O'Hara R, Mumenthaler MS, Yesavage JA. Relationship of CogScreen-AE to flight simulator performance and pilot age. Aviat Space Environ Med. 2000; 71(4):373–380.
31. Transport Canada. TP 13312 - Handbook for Civil Aviation Medical Examiners; Neurology; Multiple Sclerosis [Internet]. Transport Canada. March 2004. [Accessed 2014 Oct. 14]. Available from http://www.tc.gc.ca/eng/civilaviation/publications/tp13312-2-neurology-sclerosis-378.htm.
32. Tulving E, Thomson DM. Encoding specificity and retrieval processes in episodic memory. Psychol Rev. 1973; 80(5):352–373.
33. Uttl B. Transparent meta-analysis of prospective memory and ageing. PLoS One. 2008; 3(2):e1568.