Gaze Behavior While Operating a Complex Instrument Control Task

Michael Kalicinski; Fabian Steinberg; Marc Dalecki; Otmar Bock

INTRODUCTION: The recent developments of technology in almost all areas of industrial processing, workplace, smart homes, mobility, media, and communication change humans' everyday life environment and behavioral responses in numerous ways. Our main objective in this study was to determine whether subjects' operator performance in a complex sensorimotor task is associated with their gaze behavior.

METHODS: In two experiments subjects operated a complex control task. To this end they watched multiple displays, made strategic decisions, and used multiple actuators to maximize their virtual earnings from operating a virtual power plant. In Experiment 1 we compared gaze behavior during the tasks with respect to operator performance in two different age groups (young vs. old), and in Experiment 2 in two different gravity conditions (normal vs. microgravity).

RESULTS: We found gaze pattern changed in older subjects as well as in microgravity. Older adults and subjects in microgravity looked longer at areas that are less relevant for task success. Most importantly, these changes in gaze pattern accounted for the effects of age and microgravity and on total earnings in the instrument-control task.

DISCUSSION: In conclusion, age- and gravity-related changes of gaze behavior show a similar pattern. Gaze behavior seems to play an important role in complex control tasks and might predict alterations of operational performance.

KEYWORDS: gaze behavior, age, microgravity, realistic scenario.

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Recent developments of technology in almost all areas of industrial processing, workplaces, smart homes, mobility, media, and communication change humans' everyday life environment and behavioral responses in numerous ways. Almost all such areas require the sensorimotor system to operate and interact with different control device settings such as touch screens and other knob-based instruments. However, little is known about the interaction between sensorimotor control strategies and cognitive processing required for operating a complex instrument-control task setting, especially in a holistic and complex realistic scenario. It has been previously shown that findings from typical laboratory tasks are often not transferrable to complex realistic scenarios. This has been shown for age-related changes in sensorimotor[4] and cognitive processing,[16] and for gravity-related sensorimotor changes.[14]

We have recently introduced an instrument control paradigm to study sensorimotor and cognitive processing in their natural combination, as encountered, e.g., in modern workplace settings.[15] In this approach, subjects had to watch multiple displays and handle multiple knobs in order to optimize an outcome that was indirectly related to their sensorimotor and cognitive actions. We found performance to be lower when subjects were exposed to microgravity and this decrease was poorly associated with subjects' manual skills, acute stress responses, and mood.[15] This performance decline is of particular relevance for pilots and astronauts and thus for the successful completion of space missions. We also found that the performance of older subjects was substantially lower than those of younger ones and this performance deficit was poorly related to subjects' manual skills, cognitive functions, and their ability to learn a novel task [Dalecki M. Unpublished study; Jan. 2016]. Such a decline is especially important in regard to

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demographic change and could be a major concern for elderly pilots or industrial workers who have to operate similar control devices. Summing up, we found in both studies dramatic deficits of instrument control in microgravity and old age, but could not attribute those deficits to changes in motor performance, stress, or cognition. The question remains why the factors gravity and age affect performance in sensorimotor control tasks.

In the present study we evaluated another potential explanation for the observed deficits. Instrument control requires effective strategies for dividing attention between various displays and actuators. It is well established that the distribution of attention across visual scenery is reflected by the subjects' gaze pattern (review, e.g., in Hayhoe and Ballard[7]) and that it is degraded in old age[1,11] as well as in microgravity.[2,12] As an example, older subjects who walked in a virtual street scenario spent more time looking at the pedestrian traffic lights than did young subjects, which was interpreted as a compensatory strategy that facilitates a potential stopping response, but also degrades the ability to notice obstacles elsewhere in the visual surrounds.[3] Likewise, older persons who search for targets in the Trail-Making task use a different gaze pattern than younger ones, and this difference can explain the age-related decline in trail-making performance.[8] Finally, older subjects engage their gaze differently than younger ones during the execution of goal-directed hand movements.[6] To the best of our knowledge, corresponding research on the distribution of attention in microgravity has not yet been undertaken. However, it has been shown that the ability to distribute attention between a memory search task and sensorimotor tracking task is degraded in microgravity.[12]

Our working hypothesis posited that older participants and those exposed to microgravity would distribute their gaze across the displays and knobs of our instrument control task less efficiently, and that this deficit would be associated with their poorer performance on that task. To scrutinize this view, we analyzed eye position signals which were registered in two studies[15] [Dalecki M. Unpublished study; Jan. 2016], but had not been dealt with yet. Moreover, an additional aim of the present approach was to determine whether the well-known deficits of sensorimotor and cognitive processing in old age are comparable to deficits that emerge in the adverse environment of microgravity. This exploratory approach was based on our recent studies, in which we identified similar patterns in the elderly and in microgravity on sensorimotor aspects[16] [Dalecki M. Unpublished study; Jan. 2016]. Thus, we reanalyzed and combined our data from the two experiments that used the same complex task performed once by elderly persons and once by young and healthy subjects who were exposed to microgravity.

METHODS

Subjects

In Experiment 1, gaze was registered in the laboratory. After giving their written consent, 12 young (24.5 + 3.2 yr; 6 women) and 13 older (65.3 + 3.5 yr; 6 women) persons participated. Each participant performed 26 episodes of the instrument-control task. However, due to technical problems, gaze date was only recorded for 20 subjects. Overall task performance and grasping kinematics in this experiment were analyzed in a separate communication [Dalecki M. Unpublished study; Jan. 2016].

In Experiment 2, gaze was registered during the normal G and microgravity phases of parabolic flight. To reach near-weightlessness, a parabolic up-down maneuver has to be performed in a specialized aircraft. Each parabolic flight consisted of 30 intervals of 20 s duration under near-weightlessness (μG), alternating with 30 intervals of 20 s duration under increased weight (1.8 G) and 30 intervals of 2-8 min duration under normal weight (1 G). After giving their written consent, 12 young (28.8 + 4.8 yr; 6 female) persons participated (each performing 26 episodes per gravity condition). The subjects were trained in the whole procedure of the test 1 d prior to the flight. Due to technical problems with the first parabolic flight, gaze data were only recorded for seven subjects. In the first flight, the recording of the gaze data was not accurate (three subjects) as the calibration was not adequate. After the flight the software was updated and again tested. However, in the second flight we had a loss of gaze data for one subject due to issues during the backup process. Finally, one subject had to be excluded from the dataset due to motion sickness. Overall task performance and grasping kinematics in this experiment are analyzed in a separate communication.[15] All subjects underwent a clinical check prior to the study and received scopolamine approximately 1 h before takeoff to prevent motion sickness. The seven subjects included in the analysis did not report motion sickness during the flight.

The study protocol for both experiments was approved in advance by the local ethics committee of the university. Each subject provided written informed consent before participating. The study protocol for the parabolic flight was additionally approved by the French ethics committee of Caen. All subjects of the parabolic flight provided written informed consent during the medical check in agreement with the flight doctor.

Equipment

The paradigm has been described in full detail by our two other studies[15] [Dalecki M. Unpublished study; Jan. 2016]. The subjects sat facing seven displays and four control knobs of a simulated nuclear power plant (see **Fig. 1**). Total earnings, hand kinematics, and knob forces in this paradigm have been analyzed and communicated in the two earlier studies. Here we analyze the gaze pattern, registered by the infrared-based Tobii T60® system with a sampling rate of 60 Hz and accuracy of 0.5°. The gaze data were transformed by commercial software into dwell times within user-specified regions of interest, which were in the present study defined as actuators (knobs on the control panel), gauges (power, temperature, fuel, cooling tank, fuel rods, light, and earning displays on the screen), and irrelevant (every region outside the actuators and gauges). Fig. 1 highlights these regions of interest.

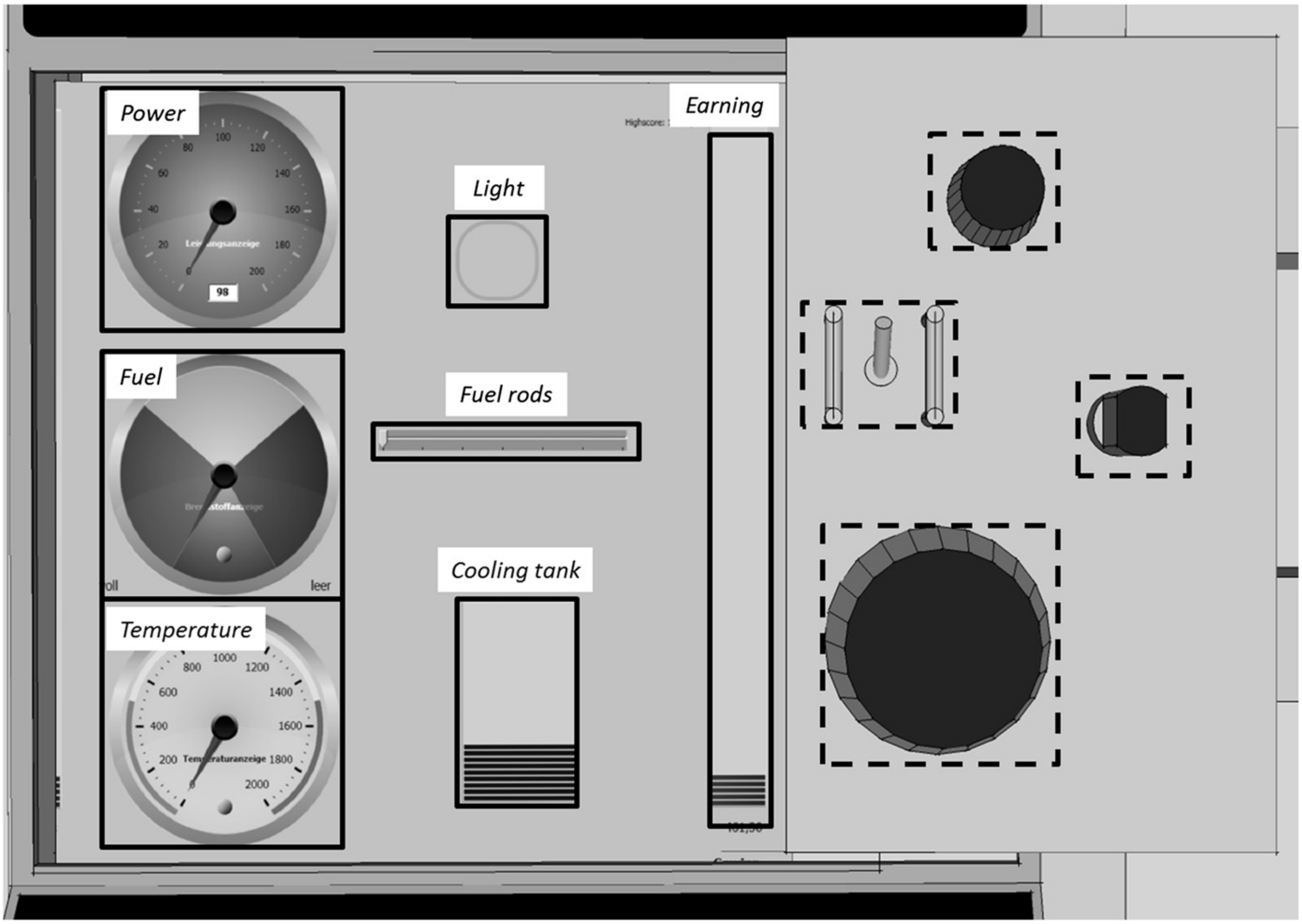

Fig. 1. Simulated power plant screen with displays on the left and knobs on the right. Regions of interest are marked in this figure (but were not seen or presented during the task), by bold (gauges) and dashed (actuators) boxes. The irrelevant region corresponds to the screen areas outside those boxes.

Procedure

A circular display at the top left indicated the momentary power production and, as an inset, the requested power production. The subjects could adjust the momentary production by rotating the larger knob, thus reducing the difference between momentary and requested production and increasing the rate of earnings. To make the task more challenging, requested production changed every 5 to 10 s, following the same sequence for all subjects. A circular display at the middle left indicated the momentary energy capacity of the fuel rod in use. This capacity decreased in proportion to the momentary power production and accordingly, a pointer rotated from the green to the red sector of the display. When it reached the red sector, the subjects had to insert a new rod such as to prevent a shutdown of the plant that would curtail their earnings. They inserted the rod by moving the rotary switch one step clockwise. A circular display at the bottom left showed the core temperature. The temperature increased proportionally with power production and, when the pointer reached the end of the red sector, the plant shut down. Thus, to prevent a loss of earnings, the subjects had to monitor the core temperature and, when necessary, refill the cooling tank displayed at the bottom center of the screen. They did so by rotating the smaller knob. A bar located at the right side of the screen showed the momentary earnings of the power plant, i.e., revenue minus expenses; the subject's task was to maximize the earnings achieved by the end of the experiment. Note that task complexity was augmented by the use of an incompatible actuator-display arrangement: the top knob controlled the bottom display, and vice versa. To prevent cognitive and muscular fatigue, the experiment briefly paused between instrument control episodes of 20 s duration.

Statistical Analysis

Gaze dwell times on actuators, displays (power, temperature, fuel, cooling tank, fuel rods, light, and earning displays on the screen*)*, and irrelevant regions were submitted to an analysis of variance (ANOVA) with repeated measures for Region [actuators, power, temperature, fuel, cooling tank, fuel rods, light, earning, irrelevant regions with the between-factor Group (young, old)] in Experiment 1, or with the within-factor Gravity (normal G, microgravity) in Experiment 2. Total earnings served as dependent variable for stepwise regression analyses with the regressors gaze dwell time on actuators, individual displays, and irrelevant regions, and 'age group' (Experiment 1) or 'gravity level' (Experiment 2). After that, semipartial correlations of the remaining regressors were used to evaluate unique associations between each regressor and total earnings. Bivariate Pearson correlations were used to analyze the direction of the relationship.

RESULTS

Fig. 2 illustrates that in Experiment 1, subjects' gaze rested mainly on the gauges, less on irrelevant regions, and rarely on the actuators. This distribution is reflected in the significant main effect of Region [$F(8, 144) = 68.52$; $P < 0.001$; $\eta^2 = 0.79$]. The significant interaction of Region × Group [$F(8, 144) = 3.18$; $P = 0.002$; $\eta^2 = 0.15$] further yielded that older persons distributed their gaze differently than the younger persons. Fisher LSD post hoc analysis showed that the older group looked significantly less on the power display ($P < 0.001$) and longer on irrelevant areas ($P = 0.0168$).

Stepwise regression revealed that total earnings were predicted by the gaze dwell time on the power and earning display, irrelevant areas, and the factor age group ($R^2 = 0.88$; $P < 0.001$). Semipartial correlations show that total earnings were predicted by the unique contributions of gaze dwell time on power ($b = 1.1$; $r_s = 0.54$; $P < 0.001$), earnings ($b = -0.62$; $r_s = -0.46$; $P < 0.001$), and irrelevant areas ($b = 0.73$; $r_s = 0.52$; $P < 0.001$), and 'age group' ($b = 0.37$; $r_s = -0.46$; $P = 0.038$), even though total earnings were strongly age-dependent when considered alone [Dalecki M. Unpublished study; Jan. 2016] [$F(1,23) = 11.55$; $P = 0.002$; $\eta^2 = 0.334$]. The other displays were discarded by the stepwise regression algorithm. Bivariate correlation analysis for the significant regressors further showed a positive association of total earnings with 'power' ($R = 0.74$; $P < 0.001$) and a negative association with the 'earnings' display ($R = -0.591$; $P = 0.006$). No significant bivariate correlation emerged for irrelevant areas ($R = -0.091$; $P > 0.05$).

As **Fig. 3** illustrates, gaze behavior in Experiment 2 was generally similar to that in the laboratory study. Gaze rested mainly on the gauges, less on irrelevant regions, and rarely on the actuators, which is reflected in the main effect of Region [$F(8, 48) = 88.2$; $P < 0.001$; $\eta^2 = 0.93$]. The distribution of gaze showed a significant Region × Gravity interaction [$F(8, 48) = 6.9$; $P < 0.001$; $\eta^2 = 0.53$], suggesting gaze is distributed differently in microgravity. Fisher LSD post hoc analysis showed that in microgravity subjects looked less at the power ($P < 0.001$) and fuel ($P < 0.001$) displays and more at irrelevant regions ($P < 0.001$) in comparison to normal G. Stepwise regression revealed that total earnings were predicted by the gaze dwell time on the power, earning, and fuel displays, and actuators ($R^2 = 0.92$; $P < 0.001$). Semipartial correlations show that total earnings were predicted by the unique contributions of gaze dwell time on power ($b = 0.67$; $r_s = 0.40$, $P = 0.01$) and earnings ($b = -0.37$; $r_s = -0.31$, $P = 0.03$). Fuel display and actuators did not reach the level of significance. The other displays, as well as the regressor 'gravity level', were discarded by the stepwise regression algorithm, even though total earnings were gravity-dependent when considered alone[15] [$F(1,18) = 4.47$; $P = 0.049$; $\eta^2 = 0.199$]. Bivariate correlation analysis for the significant regressors further show a positive association of total earnings with 'power' ($R = 0.86$; $P < 0.001$), but no association with the 'earning' display ($R = -0.287$; $P = 0.319$).

DISCUSSION

The present study dealt with the effects of older age and microgravity on gaze behavior in a realistic instrument-control task. We found gaze pattern changed in older age as well as in microgravity: in both experiments subjects looked longer at irrelevant areas and less at the power display, which was the area that provided important information to perform the task successfully. Most importantly, gaze pattern accounted for efficiency in performing the instrument-control task. Gaze pattern, therefore, seems to be a much better predictor of performance than manual skills, learning ability, cognition, stress, and mood in our earlier studies[15] [Dalecki M. Unpublished study; Jan. 2016]. This outcome is in agreement with the view that older persons and those exposed to microgravity distributed their attention across the displays and knobs of our virtual power plant less efficiently, and that this impairment could be a reason for the observed deficits of instrument control in those persons. However, it should be noted that performance declines do not necessarily depend on gaze changes alone.[13]

It is interesting to note that gaze dwell time on the 'power' display was positively associated with earnings, but that gaze dwell time on the 'earnings' display was negatively associated with earnings. Thus, although the outcome measure of our paradigm was

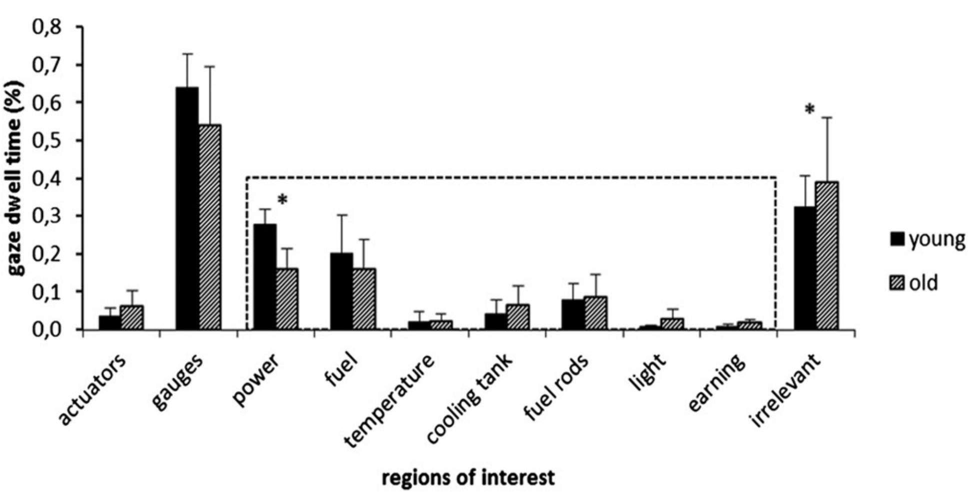

Fig. 2. Gaze dwell times separated by regions of interest and age group. Note that the box highlights the single gauges. *Indicates significant results of the respective ANOVA.

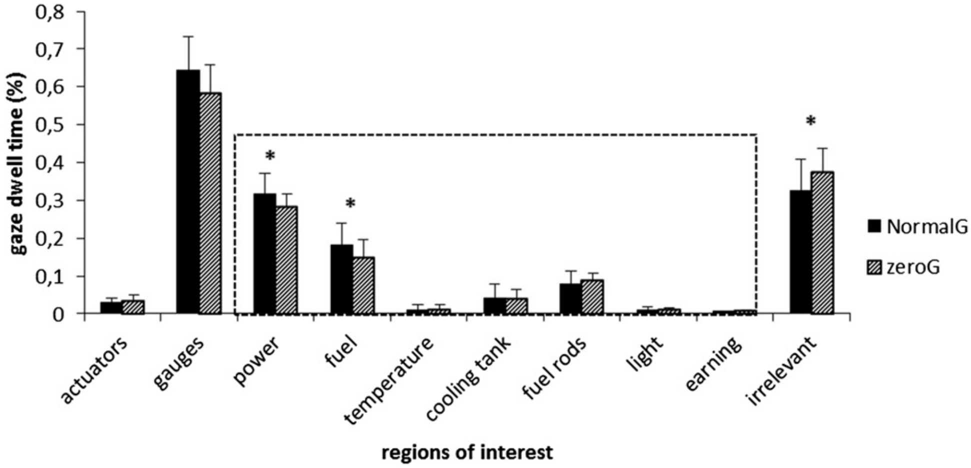

Fig. 3. Gaze dwell times separated by regions of interest and gravity. Note that the box highlights the single gauges. *Indicates significant results of the respective ANOVA.

power plant earnings, it did not pay to look extensively at the 'earnings' display. Rather, subjects might benefit from looking longer at the 'power' display, which showed the discrepancy between actual and requested power production. It would be interesting to find out whether subjects' performance would improve when their attention is drawn to the power display by instructions or by a prominent layout, or when appropriate gaze strategies are trained.[10]

Unexpectedly, older adults did not look longer at the actuators than younger ones did. Based on the documented longer knob handling times for older adults compared to younger ones in the kinematic analysis in our previous work [Dalecki M. Unpublished study; Jan. 2016], we expected them to look longer at the actuators as they may rely more on visual control when executing goal-directed hand movements. The reliance of visual control in reach to grasp movements has been previously reported. Older adults show a reduction in speed accuracy of reach-to-grasp movements when relying on visuospatial information and potentially need more time for limb selection.[6] Instead of focusing more on the actuators and 'power', older adults looked longer at irrelevant areas. This age-related change is difficult to interpret as a compensatory strategy, and rather suggests a deficit of focusing attention where it is mostly needed. Indeed, it is well established that older persons are more susceptible to distractors than young persons.[5] Susceptibility to distractors could also explain why, in microgravity, subjects looked less at the important gauges 'power' and 'fuel' and more at irrelevant areas than they did in normal gravity: microgravity is a stressful environment, and it is well known that high levels of stress increase distractibility.[9] If so, gaze behavior could be a more sensitive indicator of microgravity-induced stress than indicators such as grasping kinematics or mood, which were not significantly associated with power plant earnings.[15] Although the present study showed tentative evidence for the role of gaze behavior in control tasks, one should bear in mind that changes of operator performance and gaze behavior could be affected in parallel. Moreover, it is suggested in a flight simulator study that breakdowns in instrument scanning do not affect operator performance, but rather the ability to maintain normal gaze behavior when cognitive or mental functions deteriorate due to sleep deprivation, which might be the key for constant operator performance.[13] Finally, one could argue that the underlying mechanism responsible for a change of gaze control, although driven by different phenomena (aging, microgravity), might be somewhat comparable. An increased need for visual control due to possible deficits in visuomotor control induced by aging and microgravity might have led to changes of gaze behavior, which affects overall operator performance. Future studies should investigate if deficits in visuomotor control persist in microgravity-experienced astronauts, or rather are absent due to adaptation or compensatory strategies.

The findings of the present study could be of practical relevance for astronauts preparing for future space missions. They could help to detect deficits of gaze control, to validate the efficiency of countermeasures such as parabolic flight training, and to monitor progress as future astronauts undergo such training. Furthermore, they could form the basis of training programs targeting the age-related decay of visuomotor control and, thus, help older industrial workers to maintain their operational performance in instrument control tasks.

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