An Experimental Study of Field Dependency in Altered Gz Environments

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ABSTRACT
Failure to address extreme environments constraints at the human-computer interaction level may lead to the commission of critical and potentially fatal errors. This experimental study addresses gaps in our current theoretical understanding of the impact of $\pm Gz$ accelerations and field dependency independency on task performance in human-computer interaction. It investigates the effects of $\pm Gz$ accelerations and field dependency independency on human performance in the completion of perceptual motor tasks on a personal digital assistant (PDA). We report the results of an experimental study, conducted in an aerobatic aircraft under multiple $\pm Gz$ conditions, showing that cognitive style significantly impacts latency and accuracy in target acquisition for perceptual motor tasks in altered $\pm Gz$ environments and propose design guidelines as countermeasures. Based on the results, we argue that developing design requirements taking into account cognitive differences in extreme environments will allow users to execute perceptual motor tasks efficiently without unnecessarily increasing cognitive load and the probability of critical errors.

ACM Classification Keywords
H.1.2 User\Machine Systems: Human factors, Human information processing, Software Psychology; H.5.2 User Interfaces: Evaluation\Methodology, Theory and Methods

Author Keywords
Extreme Environments, Mobile Devices, Target Acquisition, Comparative Informatics, Perceptual Style

INTRODUCTION
When designing safety-critical systems, addressing contextual issues pertinent to where, how and why systems are used is of paramount importance. Extreme physical environments, where users typically operate under conditions of risk and stress, have a low tolerance for user error. Failure to address extreme environments' constraints at the human-computer interaction level may lead to the commission of critical and potentially fatal errors [24]. In the age of space flights and high performance aircrafts, an emerging HCI challenge is to create innovative interactive systems extending current design requirements from Earth ubiquitous $\pm 1Gz$ environment to altered $\pm Gz$ environments. Designing for extreme environments would enable users to execute perceptual motor tasks efficiently, without unnecessarily increasing cognitive load and the probability of critical errors. However, meeting such a challenge would require answering first the following question: How does context influence perceptual motor performance in human-computer interaction? Because extreme environments' stressors impact both human physiology and human psychology, the significance of understanding their synergistic effects on performance is compelling. Indeed, such an understanding would allow us to predict far more accurately than is currently possible the manner in which extreme environments' stressors affect perceptual motor performance outcomes. We argue that optimal user interface design for extreme environments such as altered $\pm Gz$ extreme environments can only be derived from such an understanding.

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RELATED WORK
Previous work on human performance relevant to the quantified prediction of human performance in extreme environments for cognitive and perceptual motor tasks exhibits a dichotomy at the theoretic level and application level. At the theoretic level, the emphasis in experimental psychology has been on human information processing models on the one hand [18, 13, 10, 41], and individual differences in the manner in which information is acquired and processed in the early stages of information processing on the other hand [44, 21]. A very brief review of theoretic models and application domains relevant to this study is presented followed by a short summary of the impact of altered $\pm Gz$ environments on human performance.

Information Theoretic Models
Several theoretic models of information processing are well suited to explaining and predicting human performance in terms of response to visual stimuli in low-level perceptual motor tasks. The Keystroke-Level Model (KLM) derived from Card, Moran and Newell's Model Human Processor [10] has been applied to a wide range of HCI tasks, and remains a simple but accurate means of generating quantitative estimates of human performance in terms of task execution time. Most appropriately, the KLM has been shown

to be a model applicable to handheld interfaces with an average prediction error of 3.7% [27]. Whenever a user must select among alternatives in a situation in which there are two or more possible stimuli, Hicks-Hyman's law provides a specific solution to model the decision outcome as a function of n possible alternatives and in terms of reaction time in target selection [18, 20]. This model also enables quantified predictions of human performance as it predicts that reaction time increases as the logarithm of the number of alternatives. Fitts' law, in its original form and in its various incarnations, has proved imminently useful in predicting speed-accuracy trade offs at the user interface level. However, although Fitts' law did provide a reliable mechanism to predict pointing time, it did not provide a direct answer to the problem of predicting error rate. Subsequent work derived from Fitts' law does provide such a mechanism [45] and can be used in conjunction with Fitts' law to predict both speed and error rate in target acquisition. Most importantly for the purpose of this study, Fitts' law, and Hicks-Hyman's law are both well suited not only to the evaluation of a wide range of pointing and selection tasks executed with the archetypal mice and trackballs pointing devices, but also to the evaluation of pointing and selection tasks executed with current tablet-stylus devices and the increasingly prevalent touch-screen devices. Just as importantly, both laws are particularly relevant in quantifying human performance in target acquisition involving both rapid, aimed movements at lower levels of information processing such as low level perceptual motor tasks on a PDA.

Field Dependency-Independency

Jean Piaget, the noted developmental psychologist, deemed the construct of field dependency independency to be a critical factor in the development of visuoperceptual analysis [33]. As a theory of individual differences in cognition, and of individual differences in information processing modalities in particular, field dependency independency theory [44] is highly relevant to the optimization of human performance in the execution of cognitive and perceptual motor tasks. Field dependency independency is typically discussed as a cognitive or perceptual style, that is as a heuristic that all individuals use to process information in their environment (e.g., color, shape, structural patterns or spatial relations), and to selectively encode this information. Furthermore, such heuristics are prevalent at numerous levels of information processing, from perceptual scanning speed in color recognition tasks to accuracy in pattern matching such as in letter selection tasks (e.g., letter comparison), and complex problem solving tasks [21].

Developed by Herman A. Witkin following a series of experiments on visual perception, the concept of field dependency independency evolved over time from "perception of the upright" to "perceptual analytical ability". In other words, the construct evolved from a narrow perceptual skill to a full fledged perceptual style in its own right [44]. As a cognitive construct, field dependence independence refers to a person's ability to separate a stimulus from its embedding context, and defines the extent to which an individual's perception of a focal stimulus is affected by distracting or conflicting contextual cues. Field independent individuals are characterized by an overt reliance on internal frames of references, while field dependent individuals are characterized by an overt reliance on external frames of reference. Operationally, field dependency independency measures the degree to which an individual has difficulty discriminating between part or parts of a field, independently of a distracting or confusing contextual field.

Theoretical indices of field dependency independency include tests of perception of the upright as instantiated in the Rod and Frame Test (RFT), and tests of disambiguation as instantiated in the Embedded Figures Test (EFT) and the Group Embedded Figures Test (GEFT). Although both tests target the same construct, they measure two different aspects of field dependency independency. The EFT and the GEFT reflect individual differences in cognitive and restructuring abilities arising from overt reliance either on undifferentiated structure or on differentiated structure in visual information processing. The RFT reflects individual differences in perception of the upright arising from overt reliance either on external visual cues or internal vestibular and somatosensory cues in information processing, in situations when vestibular cues may either conflict or conform with visual cues. These three tests have been widely used as reliable tools in numerous studies and are considered valid indicators of the ability of an individual to perceptually ignore conflicting cues in distracting, misleading, or conflicting contexts [26, 44]. Finally, Witkin [43] and his colleagues did not define field dependency independency as a binary construct but rather as a "continuum of individual differences" [26] in perceptual performance, ranging from extreme field independence to extreme field dependence. The conceptualization of field dependency independency as a perceptual style has been consistently recognized as a significant contribution to the field of experimental psychology, its influence has been pervasive in several research areas, and it has unified findings reported in many academic disciplines [22].

Safety-Critical Systems and Mission Critical Systems

The design of displays for safety-critical systems (e.g., clinical decision support systems [37]) and mission-critical systems (e.g., aviation displays [42]) has largely been implemented under the desktop level paradigm. However, very little work has been done to extend design guidelines evolved from our cumulative design experience within these two domains to mobile platforms to be used for similar purposes. Furthermore, notwithstanding the well established potential and the increased use of mobile platforms such as PDA[s] as integrated components of full fledged applications in a variety of extreme environments ranging from altered $\pm Gz$ environments, under sea habitats and space [28, 30], even less has been done to extend aforementioned design guidelines to mobile platforms for users active in such environments. As far as safety-critical systems are concerned, prior research has focused on implementing vital sign monitoring applications on a PDA in the context of high-altitude [3, 32] and altered $\pm Gz$ extreme environments [12]. As far as mission-critical systems are concerned, prior work investigated the area of RFID identification in space [9]. However, there is no indication in the literature that issues of context use, let alone individual cognitive differences, were ever given serious thought in the design and evaluation of these systems. We argue that considering both the strenuous demands extreme environments place on human physiology and their severe impact on cognitive functions, due consideration to these issues is long over due if the necessity of optimizing human performance while minimizing cognitive load and the probability of critical error is ever to be enforced at the user interface level.

Performance Degradation in Altered Gz Environments

Extreme environments can be defined as severe ecological systems well outside the range of normal human survival parameters, where optimal human performance predicated on a high level of physiological adaptation, technological innovation, and training is a sine qua non requisite for survival. Extreme environments act as physiological stressors inducing dysfunctional physiological activity. In particular, extreme environment stressors such as high acceleration loads impact both human physiology and cognition, sequentially affecting human receptors and proprioreceptors, information processing, and motor control. A significant degradation of human performance ensues, particularly conspicuous in delays and errors in task execution [41]. Nonetheless, for the user of a mission-critical or safety-critical system in altered $\pm Gz$ environments, maintaining optimal performance at all times remains a critical requirement. This combination of factors obviously places severe constraints on the use and design of mobile devices for users operating in such environments.

By convention, the capitalized letter G is used to express the inertial resultant to whole body acceleration in multiples of the magnitude of the acceleration of gravity denoted g. Traditionally, the $\pm G$ notation is used when referring to rapid transitions between positive and negative G force's values of the acceleration vector. In particular, the notation $\pm Gz$ refers to the positive or negative values of the acceleration vector along the vertical axis of the acceleration vector, i.e., accelerations parallel to the spine of the human body.

Human physiological responses to $\pm Gz$ acceleration forces are well documented in the medical literature [14, 1]. The literature discusses a constellation of physiological responses to the impact of $\pm Gz$ acceleration forces whose symptomatology can be summarized as follows: (a) an inability of the normal cardiovascular system mechanisms to provide adequate circulation to the brain and the eyes, resulting in compounded symptomatology and physiological changes; and (b) an increased normal weight hydrostatic pressure and physiological ventilation-perfusion gradients in the lungs, resulting in increased pulmonary arterio-venous shunting and subsequent impairment of circulatory oxygenation. Associated symptomatology includes, but is not limited to, arterial blood pressure fluctuations, decreased cardiac output, cardiac arrhythmias, visual disorders, reduction of peripheral vision (grey-out), total loss of vision (black-out), followed by loss of consciousness (G-LOC). Individuals exposed to rapid $\pm Gz$ accelerations experience sudden G-LOC without warning, i.e., without attending peripheral or total loss of vision [15]. Typically, G-LOC lasts for 3 to 10 seconds. After regaining consciousness, individuals typically remain disoriented for another 4 to 11 seconds [5]. Although generally perceived as a less dramatic response than G-LOC, smaller gravity fluctuations create in individuals an altered state of awareness and a number of associated cognitive impairments referred to as Almost Loss of Consciousness (A-LOC). The effects of A-LOC on cognitive functions were described as a "*disconnection between cognition and the ability to act on it*"[40]. Finally, and contrary to widely shared assumptions among aircraft pilots, research shows that exposure to $\pm G$ forces through professional training neither eliminates or diminishes physiological responses to altered $\pm G$ environments [16], and the use of anti-G suits only slightly delays the onset of "G-LOC" [15].

Different lines of research investigating the particular influence of these factors on human performance have so far reached a consensus with regard to the dynamic interdependence between extreme environments' stressors, cognition and performance. In particular, distinct lines of empirical research have conclusively shown that (a) physiological effects of $\pm Gz$ accelerations adversely impact performance [23, 17, 14]; (b) performance in $\pm Gz$ environments correlates negatively with stress [40, 16, 35]; (c) performance correlates negatively with field dependency as a perceptual style on a wide range of sensory-motor tasks [6, 7, 25]; (d) field-dependency correlates positively with stress [19, 38]; and (e) field-dependency-independency is an important determinant in human-computer interaction [8, 2]. However, a careful review of the relevant literature suggests significant gaps in our understanding of this dynamic interdependence between extreme environments' stressors, individual cognitive differences, and performance. For instance, little is known regarding interaction effects between extreme environments' physical stressors and human cognitive abilities [31]. Even less is known regarding interaction effects between field dependency independency as a perceptual style and $\pm Gz$ accelerations as an extreme environment physical stressor [29, 39]. Acknowledging these gaps in our understanding of this dynamic interdependence of variables and integrating lines of empirical research in cognitive psychology and human physiology, the experimental study reported here investigates how performance varies between field dependent and field independent groups under conditions of alternating $\pm Gz$ accelerations. The primary purpose of this research is to understand the nature and extent of the combined effects of field dependence-independence and $\pm Gz$ accelerations on human perceptual motor performance.

METHOD

Design

The experimental design is a 5x2 mixed factorial design with repeated independent measures consisting of 5 levels of the within-subjects factor (altered $\pm Gz$ accelerations of $-2Gz$, $-1Gz$, $+1Gz$, $+2Gz$, and $+3Gz$) and 2 levels of the between-subjects factor (field dependence and field independence). It involves two independent groups of participants assigned through testing to the two categories of the field dependency independency factor and randomly assigned to all five levels of the $\pm Gz$ acceleration factor.

Independent variables

The independent variables are (1) altered $\pm Gz$ environment and (2) field dependency independency. The altered $\pm Gz$ environment is operationalized as $\pm Gz$ acceleration loads corresponding to the 5 levels of the $\pm Gz$ acceleration vector coefficient used in this study. Field dependency independency is operationalized as a dichotomous variable through a block sampling strategy assigning extreme field independent and extreme field dependent participants to the two levels of the independent variable. Everything else being equal, any differences found in the measurements of the dependent variables between the two levels of the field dependency independency factor and across the five levels of the $\pm Gz$ acceleration factor can only be attributed to either interaction effects of perceptual style and $\pm Gz$ accelerations, main effect of perceptual style, and/or main effect of $\pm Gz$ acceleration.

Dependent variables

The dependent variables consist of three individual measures of human performance evaluated in terms of efficiency, effectiveness, and user interaction satisfaction. Efficiency is operationalized as latency in task execution. Effectiveness is operationalized as accuracy in task execution. User interaction satisfaction is operationalized as a self-reported score on the Questionnaire for User Interaction Satisfaction (QUIS).

Participants

A total of 18 participants participated in the study, with 9 field independent and 9 field dependent participants assigned to the two levels of the field dependent independent factor. A total of 90 non-solicited participants were included into the sampling frame after indicating their intention to volunteer for the experimental study and after taking a standard test for field dependency independency, the Group Embedded Figure Test (GEFT). This test, whose scale ranges from zero to eighteen, has been widely used as a reliable instrument in numerous studies and is considered a valid indicator of the ability of an individual to perceptually ignore conflicting cues in distracting, misleading or conflicting contexts. A typical sampling strategy is to use a theoretical index of field dependency independency such as the GEFT to rank participants on the field independency dependency continuum and to use the median score to divide them into two groups. Participants whose score falls on or below the median are assigned to the field dependent group, while participants whose score falls above the median are assigned to the field independent group. However, in order to create two groups of extreme field dependent and extreme field independent participants, this study enforced block sampling as an alternate strategy. Accordingly, a sample of 18 participants was drawn out of the original pool of 90 participants included in the sampling frame. The field dependent experimental group consisted of 9 participants who scored between 0 and 9 of the GEFT, and the field independent experimental group consisted of 9 participants who scored between 17 and 18. Due to safety concerns, and to control for a potential confounding variable in the experimental design, participants screened for vestibular disorders were excused from the sampling frame as they could have experienced dizziness, vertigo, imbalance, and nausea during the experiment. Participants received no compensation for their participation.

Demographics

Average age of field independent participants was 28.89 years (Range:$19-39, SD=5.71$). The field independent group consisted of 7 non-pilots and 2 pilots. Of the 9 field independent participants, 5 were male and 4 female. Average score on the Computerized Rod and Frame Test (CRFT) was 0.35 (Range: $0.20-0.54$, $SD=0.11$, $SE=0.03$). On the Group Embedded Figure Test (GEFT), the primary measure of field dependency independency, participants scored an average of 17.33 (Range: $17-18$, $SD=0.50$, $SE=0.17$).

Average age of field dependent participants was 31.89 years (Range: $23-64$, $SD=13.28$). The field dependent group also consisted of 7 non-pilots and 2 pilots. Of the 9 field dependent participants, 6 were male and 3 female. Average score on the Computerized Rod and Frame Test (CRFT) was 0.81 (Range: $0.13-2.00, SD=0.56, SE=0.18$). On the Group Embedded Figure Test (GEFT), the primary measure of field dependency independency, participants scored an average of 7.22 (Range: $4-9, SD=1.86, SE=0.62$).

No significant differences were observed between the experimental groups on age, pilot experience and gender. As expected, a one-way analysis of variance with respect to CRFT scores was significant ($F(1,17)=5.68, p=0.03$). Similarly, a one-way analysis of variance with respect to GEFT scores was significant ($F(1,17)=249.05, p<0.0001$).

Apparatus

The experiment was conducted in a CAP10B aerobatic aircraft, with participants interacting with a Dell Axim^{TM}X51v PDA secured to their left or right thigh to a NavPad^{TM}support system. The CAP10B comes with side-by-side seating, dual control configuration and is stressed to $+6$Gz and -4.5Gz. The Dell Axim X51v PDA runs Windows Mobile 5 on a 3.7" LCD with a 640x480 resolution VGA display. The in-flight support system for the PDA is a hard plastic mount designed to support a PDA on the left or right thigh of the participant. The PDA attaches with Velcro^{TM}to the front-top surface of the NavPad^{TM}. The mount is then secured to the participant thigh with a Velcro strap. The NavPad is designed to hold the PDA at a 30 degree angle, presenting to the participant a clear view of the screen at all times. The experimental set up including the the PDA and the NavPad mount secured to a participant's thigh is presented in Figure 1.

The selection of a PDA as the mobile computing platform for the experimental study was dictated by theoretically driven requirements – touchscreen interface, screen size and resolution, related studies [3, 32, 28, 30] – as well as more pragmatic concerns – availability, architecture, programmability, safety concerns, ergonomic issues for participants, and restricted accommodation capabilities of the aerobatic aircraft.

Figure 1. Experimental Setup

The selection of a high performance aerobatic aircraft for the experimental study was dictated by ecological validity concerns.

Tasks

Participants in the experiment were asked to execute three tasks. The first task was a button selection task, the second task was a letter selection task, and the third task was a field dependent independent task.

Button selection task

The first task is designed to evaluate and compare participants' performance in selecting a single red button randomly displayed within each of the four tasks' configurations. Four

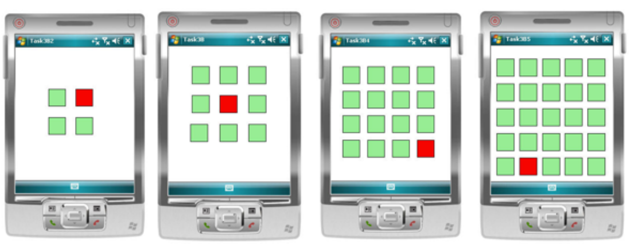

Figure 2. Button Selection Task

different configurations of the button selection task are presented in random order to the participants. Each button selection task configuration on the screen displays either 4, 9, 16, or 25 buttons arranged in a grid layout pattern. Figure 2 shows an example of a randomly generated red button task sequence.

Participants are instructed to select the red button as quickly and as accurately as possible. Immediately after selection, or after a three second time-out, the screen displays the next task to the participant. Each event of the button selection task times out after being displayed for three seconds.

Letter selection task

The second task is designed to evaluate and compare participants' performance in identifying and selecting a single letter of the Roman alphabet randomly displayed within each of the four tasks' configurations. The letter to be selected

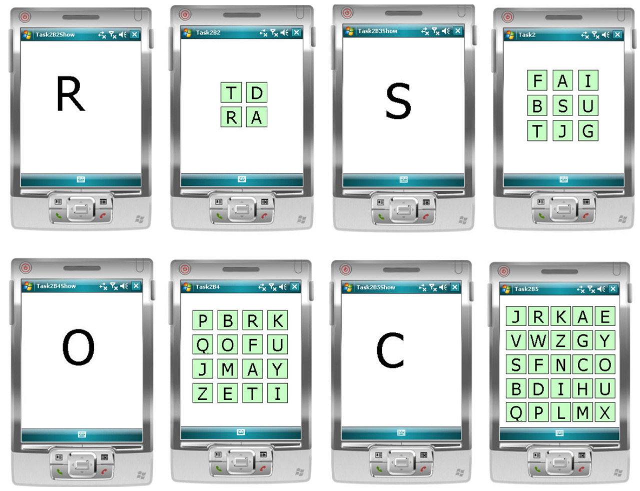

Figure 3. Letter Selection Task

is first displayed by itself in the center of the screen for a duration of one second. Immediately thereafter, one of four different randomly selected letter grid layout screens is presented to the participant. Each configuration on the screen displays either 4, 9, 16, or 25 non-repeated letters arranged in a grid layout pattern defining each of the four letter selection tasks' configurations.

Immediately after selection, or after a three or four seconds time-out, the screen displays the next task to the participant. The second task times out at three seconds for all but the 5x5 task configuration. Due to floor effect observed in pilot studies in the 5x5 letter selection task configuration, the time out for this particular task configuration was increased to four seconds. Figure 3 shows an example of a randomly generated letter selection task sequence with its random combinations of letter and letter grid layout.

Field Dependent-Independent task

The third task, implemented around the rod and frame illusion (RFI), is designed to evaluate and compare participants' performance in spatial orientation against a baseline previously established on the ground.

The orientation of a vertical rod when viewed in the context of a tilted frame is typically misperceived as the result of the tilt of the frame. Since the rod and frame illusion is leveraged as a test of field dependency-independency in the rod and frame test (RFT) [44] this task also compares participants' performance against a baseline previously established on the ground through the administration of the RFT. One of the two randomly selected rod and frame events is first displayed by itself in the center of the screen for a duration of two seconds. Immediately thereafter, a second screen is presented to the participant asking *"Was the rod tilted"*. The participant has two seconds to answer the question by selecting either one of two buttons labeled "Yes" or "No". Figure 4 shows each of the two possible field dependent independent task configurations and the associated question screen.

Unknown to the participant, the rod is invariably set exactly to the vertical in each task event. Each event of the field dependent independent task times out at four seconds.

Figure 4. Field Dependent-Independent Task

As explained in the Design section, all three tasks were presented to all participants at each of the five levels of the $\pm Gz$ factor. Each and every specific task's configuration as well as its order of presentation was randomly generated before being hard coded into five different task sequences. At any particular $\pm Gz$ level, the tasks were presented to the participants within the same unique tasks' configurations sequence assigned to this particular $\pm Gz$ level. It follows that (a) at a specific level of the $\pm Gz$ factor all participants to the experiment were presented with exactly the same unique task sequence featuring the same tasks configurations presented in the same order, and (b) each of the five $\pm Gz$ level specific task sequences displayed in a different order nine tasks configurations unique to this particular sequence. At each level of the $\pm Gz$ factor the entire task sequence timed out at 29 seconds.

To control for nausea at all $\pm Gz$ levels, participants were to report on the PDA at the end of each task sequence their subjective wellness state before being allowed to continue the experiment. The PDA "start up" and "wellness" screens are shown in Figure 5. No participant to the experiment ever became nauseated or reported feeling bad.

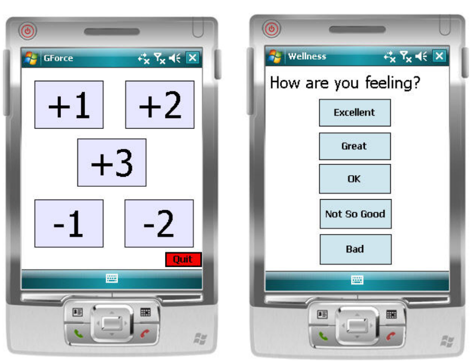

Figure 5. PDA Start-Up and Wellness Screen

Hypotheses

Based on available empirical evidence and a careful review of the literature on individual differences and $\pm Gz$ acceleration physiology, the following three hypotheses were advanced:

H_1 There will be a statistically significant interaction effect in performance between the $\pm Gz$ accelerations factor and the field dependency field-independency factor on the button selection and letter selection tasks.

H_2 Performance will be significantly lower at altered $\pm Gz$ acceleration levels than at the $+1Gz$ acceleration level on the button selection and letter selection tasks.

H_3 Performance will be significantly lower for field dependent participants than field independent participants on the button selection and letter selection tasks.

Data Collection

For each task event, both latency and accuracy in task execution were recorded. All experimental data was logged in to a CSV file. The data output file opened at the beginning of each task, was written to as the time of task completion, and was closed immediately afterward, so all data was recorded even in the case of abnormal termination of the program.

Procedure

To ensure both familiarity with the software and the tasks, all participants were instructed on how to run the application and were trained on a demo task sequence before the flight. All participants were asked to execute the tasks as accurately and as quickly as possible before running the application on the ground and as a last reminder just before take-off. Participants to the experiment were seated in the co-pilot seat of a CAP10B aerobatic aircraft with the PDA strapped to their left thigh if they were left handed, or right thigh if they were right handed. This is a standard interactive mode for reading and writing notes for pilots and co-pilot of an aircraft.

Each participant to the experiment flew at all 5 Gz levels in the same sequential order: $+1Gz$, $+2Gz$, $+3Gz$, $-1Gz$ and $-2Gz$. At each Gz level, after setting the aircraft into the appropriate Gz flight pattern, the pilot confirmed to the participant the Gz level value and instructed the participant to begin the tasks sequence with the simple instruction: "*Start!*". After selecting the appropriate Gz level button on the PDA start-up screen, the participant executed the entire tasks' sequence for this Gz level. Immediately after completing the task sequence for a particular $\pm Gz$ level, the participant allowed the pilot to unload the $\pm Gz$ and resume $+1Gz$ normal flying conditions with the simple call: "*All done!*". The pilot then returned for one minutes to a normal $+1Gz$ flight pattern to allow the participant's physiology to return to normal before exposure to the next $\pm Gz$ level.

RESULTS

Results are organized under the following four sections: hypotheses testing, field dependent independent task, wellness, and user interface satisfaction.

Hypotheses Testing

Latency

A mixed factorial repeated measures multivariate analysis of variance of latency in task execution showed no statistically significant interaction effects between the field dependency independency factor and the altered $\pm Gz$ acceleration factor for latency ($Roy's\ largest\ root = 0.142, F(4, 13) = 0.461, ns$). Thus, the first hypothesis H_1 was not supported. However, hypothesis H_2 and H_3 were supported. Analysis showed a significant main effect of the within subjects $\pm Gz$ accelerations factor on latency (H_2) ($Roy's\ largest\ root = 2.572, F(4, 13) = 8.358, p < 0.001,\ partial\ \eta^2 = 0.72,\ observed\ power = 0.982$. As predicted, performance on both the button selection and letter selection tasks worsened under altered $\pm Gz$ acceleration conditions compared to the $+1Gz$ condition. Figure 6 presents average time, in milliseconds, on the combined button selection and letter selection tasks across the five levels of the altered $\pm Gz$ acceleration factor. The error bars display 95% CI of the means. Analysis showed a significant main effect of the between

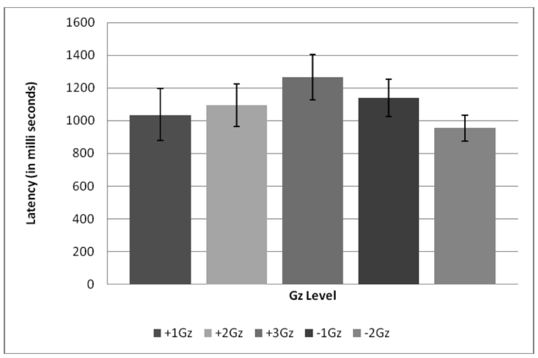

Figure 6. Latency Across Altered Gz Levels

subject field dependency independency factor on latency (H_3) ($F(1, 16) = 4.644, p = 0.047$, partial $\eta^2 = 0.225$, observed power $= 0.526$). As predicted, field dependent participants took more time than field independent participants on both the button selection and the letter selection tasks. Figure 7 presents presents average time, in milliseconds, taken by the field independent group versus the field dependent groups.

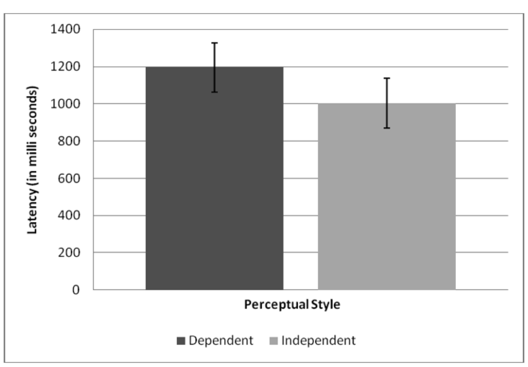

Figure 7. Latency between the Experimental Groups

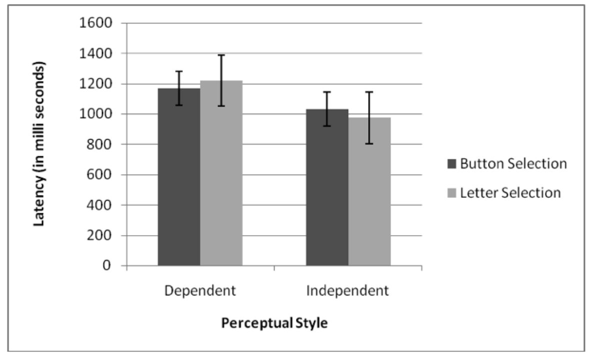

Figure 8. Latency between the Experimental Groups by Task Types

Figure 8 presents the results for latency across the two perceptual style groups for the two task types. Furthermore, results show that task complexity (2x2, 3x3, 4x4, 5x5) increased latency. Figure 9 presents results across task complexity levels.

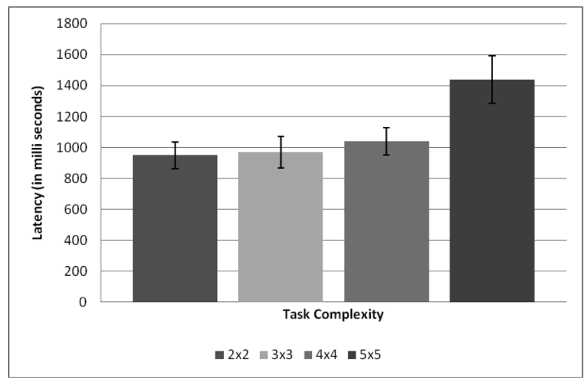

Figure 9. Latency between the Experimental Groups by Task Complexity

Accuracy

A mixed factorial repeated measures multivariate analysis of variance of accuracy in task execution showed no statistically significant interaction effect between the field dependency independency factor and the $\pm Gz$ acceleration factor ($Roy's\ largest\ root = 0.267, F(4, 13) = 0.868, ns$. No significant differences were observed on accuracy for the $\pm Gz$ accelerations within-subjects factor. Marginally significant differences in accuracy were observed between the field dependent and field independent experimental groups ($F(1, 16) = 3.866, p = 0.067$, partial $\eta^2 = 0.195$, observed power $= 0.456$). Accuracy was higher for field dependent participants on the button selection task whereas field independent participants scored higher on accuracy on the letter selection task.

Field Dependent-Independent Task

Significant differences on latency for the field dependent independent task were observed between the two experimental groups at the $+1Gz$ level and at none of the other 4 altered

$\pm Gz$ levels. Accuracy on the task was not significantly different between the two experimental groups at any of the 5 $\pm Gz$ levels.

Wellness

Participants self-reported high scores on wellness across the five levels of the altered $\pm Gz$ accelerations factor with no significant differences observed between the field dependent and field independent experimental groups or across the levels of the $\pm Gz$ accelerations factor. Therefore, both motion sickness and nausea can be ruled out as potential confounding factors in the experimental study.

User Interface Satisfaction

The QUIS questionnaire [11] was administered to collect the participants' subjective satisfaction scores. The QUIS 7.0 instrument also measured participants' subjective satisfaction with the instructions and the tutorial, aside from various system measures. No significant differences were observed on any of the sections of the QUIS instrument.

DISCUSSION

The experimental results support the hypothesis that performance for field dependent participants is significantly lower than for field independent participants on the button selection and letter selection tasks. As such, it is clear that in altered $\pm Gz$ environments individuals' mode of information processing has a significant impact on perceptual motor performance when interacting with the touchscreen interface of a mobile device. This study's findings corroborate the impact of $\pm Gz$ acceleration on task performance documented in prior research. For example, an experimental study investigating the effects of $\pm Gz$ acceleration on cognitive performance showed performance degradation across individuals on a compensatory tracking task, a system monitoring task, and a strategic resource management task [29]. The results of our study suggests that field dependent individuals would benefit from mobile displays that provide support for disambiguation of objects and artifacts in a perceptual field. The experimental results also support the hypothesis that performance on the button selection and letter selection tasks is significantly lower in altered $\pm Gz$ environments than on Earth's ubiquitous $+1Gz$ environment. This finding corroborates prior general findings on the impact of altered $\pm Gz$ environments on human performance and firmly establishes their relevance at the human computer interaction level. The study's findings corroborate the impact of perceptual style on task performance documented in prior research. For example, an experimental study investigating the relationship between perceptual style and tracking ability showed that among U.S. army pilots, field dependent individuals had significantly more difficulty than filed independent individuals in tracking an object similar in color to its background [4]. The results of our study suggest that users of mobile devices in $\pm Gz$ environments would benefit from displays featuring an interface adaptive to altered $\pm Gz$ environments. The experimental results failed to support hypothesized interaction effects between altered $\pm Gz$ environments and field dependency-independency. This suggests that the impact of altered $\pm Gz$ environments on human physiology and individual differences in information processing operates at different levels with little cross-level interaction. Each of these factors influences human performance but there is no empirical evidence to indicate that they significantly impact each other. The results illustrate how environment independent and individual homogeneity design assumptions can contribute to significant degradation in performance in situated human computer interaction. They suggest the need to develop and test innovative user-interface design requirements for mobile devices aimed at mitigating the effects of altered $\pm Gz$ and individual differences on human performance. They also demonstrate the need to develop adaptive displays addressing both the constraints altered $\pm Gz$ environment place on users, and the differences in information processing among users. A two pronged approach to the problem might indeed be more productive of a solution than either approach in isolation.

Implications for HCI

Historically, HCI has witnessed an evolution with regard to context of use. While HCI was originally concerned with the desktop and desktop applications, the scope of its application has considerably widened with the emergence of ubiquitous computing. As a result, its domain of inquiry has become increasingly more diversified. We already know that mobile devices break many assumptions inherent to HCI and desktop computing [36]. However, we know very little as to how performance in HCI covaries with the constraints imposed by the environment. As such, the HCI community might consider a proactive research agenda with regard to mobile computing in extreme environments. Indeed, the evidence is that mobile devices have a promising future in extreme environments as their increasingly ubiquitous presence in such environments suggests. For instance, professional users increasingly require mobile computational devices when working in extreme environments as diverse as deep-sea diving [28], high altitude [3] or space [9]. The same could be argued with regard to the increasing propensity of recreational users to use mobile devices as consumer products (e.g., GPS) in extreme recreational environments activities as diverse as sky-diving, high performance flying, scuba-diving or high altitude climbing — to name a few. Furthermore, one of the primary goals of usability is safety [34], and as this paper pointed out extreme environments are always characterized by conditions of risk and stress. As such, for users of mobile devices immersed in such environments, safety-critical issues become of paramount importance, life-critical in fact. Finally, if any claims to ecological validity can legitimately be made, HCI needs to research these issues in their extreme environment context of use. The facts are that (a) mobile technology is increasingly ubiquitous in extreme environments; (b) mobile devices are a logical platform for users to choose in such environments; and (c) this steady trend among users creates a host of HCI concerns that beg to be addressed. For the aforementioned reasons, the authors feel that there are urgent, tangible, and promising research opportunities for HCI researchers to contribute their expertise to, in an effort to address what we see as a new challenge emerging on the HCI horizon.

FUTURE WORK

The long term purpose of this line of research is to enable users of mission-critical and safety-critical systems in altered $\pm Gz$ environments to execute low level interaction tasks quickly and efficiently, without unnecessarily increasing cognitive load and the probability of critical errors. A particularly promising application domain specifically requiring individuals to be mobile while using small, lightweight computing devices, lies within space's zero Gz environment. As a case in point, to allow space crews to perform mission-critical tasks, both the ESA and NASA are increasingly relying on mobile computing platforms, and particularly on PDA[s]. They are also relying increasingly on these mobile platforms to perform safety-critical tasks such as monitoring crew members' vital signs. To extend this research to zero Gz environments, the authors have initiated preliminary negotiations with NASA to establish modalities of use of NASA Ames' C9-B parabolic aircraft which would simulate a near zero Gz environment for future experiments.

CONCLUSION

This experimental study analyzed the main effects and interaction effects of altered $\pm Gz$ accelerations and individual differences in perceptual style on performance. The study showed that both $\pm Gz$ accelerations and perceptual style significantly impact human performance. The findings could help predict in an accurate manner how altered $\pm Gz$ environments and individual differences in information processing impact human performance. The findings could also provide guidelines for the design of interactive mobile computing platforms used in altered $\pm Gz$ environments. Additional experimental evidence would help in the development of a theory of human-computer interface design in extreme environments.

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