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Understanding the structure of skill through a detailed analysis of Individuals' performance on the Space Fortress game

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ABSTRACT

In this paper we describe a novel approach to the study of individual differences in acquired skilled performance in complex laboratory tasks based on an extension of the methodology of the expert-performance approach (Ericsson & Smith, 1991) to shorter periods of training and practice. In contrast to more traditional approaches that study the average performance of groups of participants, we explored detailed behavioral changes for individual participants across their development on the Space Fortress game. We focused on dramatic individual differences in learning and skill acquisition at the individual level by analyzing the archival game data of several interesting players to uncover the specific structure of their acquired skill. Our analysis revealed that even after maximal values for game-generated subscores were reached, the most skilled participant's behaviors such as his flight path, missile firing, and mine handling continued to be refined and improved (Participant 17 from Boot et al., 2010). We contrasted this participant's behavior with the behavior of several other participants and found striking differences in the structure of their performance, which calls into question the appropriateness of averaging their data. For example, some participants engaged in different control strategies such as "world wrapping" or maintaining a finely-tuned circular flight path around the fortress (in contrast to Participant 17′s angular flight path). In light of these differences, we raise fundamental questions about how skill acquisition for individual participants should be studied and described. Our data suggest that a detailed analysis of individuals' data is an essential step for generating a general theory of skill acquisition that explains improvement at the group and individual levels.

1. Introduction

Theories of skill acquisition have primarily focused on the changes in performance that generalize across tasks as a function of amount of practice (Anderson, 1982, 1987; Fitts & Posner, 1967; Newell & Rosenbloom, 1981). Research in this tradition often analyzes overall performance, such as task completion time, number of errors, game scores, etc., averaged across all participants in a given training condition, a methodology that we will refer to as the "group-comparison approach." Some researchers have examined individual differences in performance among participants by correlating performance after different amounts of practice with individual differences in basic cognitive capacities or stable abilities (Ackerman, 1992). We will contrast this predominant approach with a second approach, which we call the "individual-analysis technique." This approach involves the detailed analysis of individuals in order to identify the specific mechanisms and behaviors that mediate their performance on the practiced task. Rather than search for individual differences in cognitive capacities to explain differences in performance, this technique is consistent with the expert-performance approach, which focuses on identifying the acquired mechanisms that mediate objectively superior performance through careful analysis of individual performers (Ericsson & Smith, 1991; Ericsson & Ward, 2007).

These techniques have typically remained distinct and it is rare for them to be applied together to understand skill development. However, we argue that it is important to find ways to integrate these two approaches to reach a consensus about the relative importance of factors influencing skill development, the relationship between general ability measures and complex task performance, and the methods and strategies that foster the development of high levels of skill (Detterman, 2014; Ericsson, 2014; Ericsson, Roring, & Nandagopal, 2007). The primary goal of the present study is to apply the individual-analysis technique to data that have previously been analyzed with the group-comparison technique to more fully understand the nature of skilled performance and that factors that contribute to it within a domain.

1.1. A brief historical background

One critical difference between the individual-analysis and group-comparison techniques is the necessary assumption that performance

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within groups is homogenous, and that skill acquisition proceeds in predictable ways towards automaticity. In 1897 Bryan and Harter found a consistent pattern of skill acquisition in telegraph operators that was similar across hundreds of individuals. Since skill was progressing similarly and learners were largely approaching the task in the same way, meaningful comparisons between groups of learners could be made, a finding that conforms to the assumptions of the group-comparison approach. However, later research focusing on outcomes of experimental manipulations between groups of participants often found considerable inter-individual differences in both the amount of improvement of performance as well as in their final performance level (see Speelman & Kirsner, 2005, for a review).

Later, researchers turned their attention to complex problem solving tasks that could be administered in the laboratory, and found that systematic individual differences in the strategies participants reported correlated with task performance in popular experimental tasks such as picture verification (Mathews, Hunt, & Macleod, 1980), paired-associate learning (Bower & Winzenz, 1970), and backward digit-span (Dempster, 1981). These studies highlight some of the deficiency of the group-comparison technique as a method to uncover the structure of skill and give us valuable insight into the underlying structure of skill beyond what can be learned through the group-comparison technique. They also raise critical questions about the homogeneity of behaviors and the assumptions of automaticity in complex laboratory tasks. We argue that this individual-analysis technique, which has been mostly used in research on expert skill can be successfully extended to laboratory studies of skill acquisition to supplement the more common group aggregate approaches.

1.2. Applying the individual-analysis technique to the domain of Space Fortress

The individual-analysis technique can be thought of as an extension of the expert performance approach, which was outlined by Ericsson & Smith (1991) to study the structure of experts' superior skill. The expert-performance approach recommends an analysis of skill through a progression of stages. The first stage is to confirm an individual's objective level of performance under standard conditions. In domains such as chess, music, typing, and sports, there are well-established methods for attaining objective performance measures such as selecting the best move from a given chess position or reliably performing a standard piece of music (see Ericsson, Krampe, & Tesch-Römer, 1993). Similarly, in complex laboratory tasks, it is possible that individuals' repeated performance under standard conditions could show reproducible performance that is superior to other participants.

The second step in the expert-performance approach is to identify candidate mechanisms that can explain the observed skill differences. Traditional applications of this approach involve process-tracing methods such as verbal reports (Ericsson & Simon, 1980) or detailed analyses of behavioral data (see Ericsson & Smith, 1991). For example, studies of chess have shown that skilled players develop domain specific memory structures and perceptual strategies that differ from less skilled players (Reingold, Charness, Pomplun, & Stampe; 2001; Chase & Simon 1973). In complex laboratory tasks, researchers can identify places where participants encounter similar situations and analyze these encounters to determine the structure of their changing behavior and increased performance. The final step in this approach is to understand how individuals acquired the relevant mechanisms through experience and training and how much individual differences in these mechanisms depend on stable traits.

This approach has been successful at revealing the mechanisms that mediate the acquisition of high levels of performance in a variety of domains. Studies in chess, music, memory, and typing, to name a few examples, have revealed that performance in each domain is primarily mediated by domain-specific mechanisms that do not generalize to other domains and show very limited transfer (Chase & Simon, 1973; deGroot, 1978; Ericsson et al., 1993; Salthouse, 1984).

We believe that aspects of the expert-performance approach can be successfully applied to research on complex laboratory tasks. We provide evidence from a widely used task, the Space Fortress video game, that individual behavior can be analyzed to provide detailed information about changes in a given participant's performance that would not be apparent when analyzed by the traditional group-comparison technique. Previous studies have investigated strategy differences in commercially available games with retrospective interviews of players, but these studies often include only short durations (10 min) of gameplay (Blumberg, 2000, Blumberg & Sokol, 2004). Other studies have used think-aloud data generated during about 20 min of gameplay to uncover differences in problem solving strategies (Blumberg & Randall, 2013; Blumberg, Rosenthal, & Randall, 2008; Zhang, Blumberg, Shen & Su, 2009). While interesting, these studies examined only relatively short training experiences and the parameters describing performance for the commercial games are not well understood in terms of the underlying psychological mechanisms.

The Space Fortress game is an ideal complex task for studying individual behavior because it was designed by cognitive scientists to address the problem of integrating findings from many laboratories for investigating skill development on very different tasks. Space Fortress was developed by researchers working on the Learning Strategies project funded by DARPA (Donchin, 1989). Their goal was to design a complex task environment that would allow researchers to examine skill acquisition over the course of 30+ hours with well-described parameters and the ability to compare results across laboratories. As a result, the Space Fortress game has been widely used by researchers interested in training and transfer-of-training. In fact, Google Scholar returns 596 results for that search term “Space Fortress”.

Briefly, Space Fortress integrates several cognitive tasks that require execution of psychomotor, perceptual, and memory skills (Mané & Donchin, 1989). The game requires players to use a joystick to pilot a ship through a two-dimensional frictionless environment while trying to destroy a “fortress” in the center of the screen that tracks and fires missiles at the ship. Controlling the ship is difficult and requires extensive coordination to apply the correct combinations of thrusts and turns to orient towards the fortress and avoid being hit by the fortress' missiles. Players' primary goal is to destroy the fortress as many times as possible within each three-minute game, but there are several other tasks, which require the player to execute complex series of behaviors and attend to many different features at once (see Section 2.1.3 for more information).

The Space Fortress game has been successfully used for studying everything from disintegrated training regimens (Frederiksen & White, 1989, Gopher, Weil, & Siegel, 1989) to transfer of learned skills to measures of intelligence, memory, and psychomotor ability (Boot et al., 2010; Lee et al., 2012). Many interesting Space Fortress studies have focused on identifying the most effective training conditions for the task. These studies typically show an advantage of part-task and shifting emphasis training over whole-task training, where separate aspects of the game are emphasized at different times (Boot et al., 2010; Frederiksen & White, 1989; Gopher, 2007; Gopher et al., 1989; Lee et al., 2012). While these studies have increased our understanding of the conditions under which groups' performance can be increased, they have not analyzed the associated changes in the performance on the individual level.

1.3. Hypotheses

In this paper we apply the individual analysis technique to Space Fortress and provide a detailed behavioral analysis of a small set of individuals selected from large groups of participants available from archival data collected at the University of Illinois Urbana-Champaign (Boot et al., 2010). We analyze and contrast the performance of one of the most skilled Space Fortress players in the literature who we refer to as