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Individual differences and workload effects on strategy adoption in a dynamic task

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ABSTRACT

The current study investigated the effects of individual differences and workload on strategy adaptivity in a complex, dynamic task called the Space Fortress game (Donchin, 1989). Participants learned to use a strategy of flying a ship in circles around the fortress in a standard game environment. Once they mastered the strategy, they were assigned to different workload conditions and transferred to a nonstandard environment in which a strong wind was introduced that made it more difficult to achieve a circular orbit. About half of the participants continued with their prior circular strategy while the rest adopted a novel strategy that achieved comparable performance with less effort. With this novel strategy, rather than trying to complete orbits they flew into the wind and then allowed the wind to blow them back to achieve a pendulum-like path. Participants without a working-memory load were more likely to adopt the new strategy. Participants were also more likely to adopt the new strategy if their pattern of behavior exposed them more often to the potential of drifting with the wind. The results indicate that spontaneous changes in strategy occur when people are exposed to the potential of a new strategy and have the cognitive resources to understand its potential.

1. Introduction

The current study investigated factors influencing strategy use in a complex real-time task. We focused on a circumstance in which individuals who already have a well-learned strategy face a novel environment in which the learned strategy becomes difficult to implement successfully. This circumstance is common in everyday settings. For instance, learning how to drive involves learning to execute a set of procedures in the correct sequences and fine-tuning the associated parameters (e.g., how much acceleration is needed to achieve 50 mph). After some practice, the combination of the procedures and the associated parameters allows one to achieve a reasonable level of performance. However, the driving strategy acquired under normal road conditions may not work successfully when one drives on icy roads. Faced with the change, one can still maintain the learned strategy by adjusting the parameters (e.g., decreasing the vehicle speed and applying smoother acceleration). Alternatively, one can deviate from the learned strategy and adopt a novel strategy geared to the constraints of the new environment. Instead of trying to control the car on icy roads according to the learned strategy, one can let momentum carry the car over the slippery patch and the driver can then steer into the skid.

Studies of human problem solving have shown that people often adopt a new, more efficient strategy or select between available strategies to adapt to various task requirements (Lovett & Anderson, 1996; Lovett & Schunn, 1999; Reder, 1987; Siegler, 1988; Walsh & Anderson, 2009). People strategically chose between mental computation and calculator use depending on problem difficulty and calculator responsiveness (Walsh & Anderson, 2009). People show adaptive strategy use not only in static problem solving tasks but also in dynamic tasks (Best, Schunn, & Reder, 1998; John & Lallement, 1997; Reder & Schunn, 1999). For example, participants learned to use a more efficient strategy that saved the number of key presses in the Kanfer–Ackerman Air Traffic Controller task (Lee, Anderson, & Matessa, 1995). However, people do not always adopt a better strategy (Fu & Gray, 2004; Schunn & Reder, 1998). This seems particularly likely when they have to change a well-practiced strategy to adapt to a new environment (as in driving on an icy road). If only some people discard the well-practiced strategy and adopt an alternative strategy, the question is what factors explain those who do and those who do not. We investigated two factors: Workload and individual differences in strategy use.

Workload is defined as the cost or demands that one experiences in achieving a specific level of performance. Workload can be detrimental to performance as more investment of resources on a task makes fewer resources available for performing other activities (Mane & Wickens, 1986). Negative effects of workload have been observed in various tasks ranging from dynamic decision making (Gonzalez, 2005), perceptual-motor skill (Morris & Leung, 2006), and mathematical problem solving (Sweller, 1988). The cognitive load theory (Sweller, 1988; Sweller, van Merrienboer, & Paas, 1998) claims that successful learning depends on minimizing unnecessary working-memory load. The effects

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of workload can be especially critical in non-normal situations in which people need to deal with unexpected changes in the environment. For example, severe turbulence encountered during flight will impose increased workload on a pilot. In addition to flying the aircraft, the pilot may need to check a radar system to find a safer route to fly and communicate with air traffic control system.

Several studies investigated the relationship between cognitive capacity and strategy selection in reasoning and problem solving tasks. In MacLeod, Hunt, and Mathews (1978), individuals with higher spatial ability chose to use a spatial strategy rather than a verbal strategy in a sentence-picture verification task. The authors claimed that individuals chose strategies based on their rational estimate of capabilities. Reichle, Carpenter, and Just (2000) found significantly negative relations between strategy-related cortical activation (e.g., language-related regions) and psychometric performance (e.g., reading span). Based on capacity-constrained view of working memory (Just & Carpenter, 1992), the authors predicted that people should prefer strategies that minimize cognitive workload. In Beilock and DeCaro (2007), individuals with higher working-memory capacity were more likely to use computationally demanding processes than individuals with lower working-memory capacity did in solving complex math problems. Roberts, Gilmore, and Wood (1997) found that in a reasoning task in which a spatial strategy was less efficient than a cancellation strategy, individuals with high spatial ability adopted the cancellation strategy instead of the spatial strategy. They claimed that individuals with high spatial ability were able to construct a more accurate, stable representation of the task, which further allowed them to develop a more efficient strategy.

A limited-capacity view (Brooks, 1968; Kahneman, 1973; Navon & Gopher, 1979) predicts that high workload would negatively affect the ability to adopt an alternative strategy in skill performance. Trying to improve one's strategy creates a dual-task situation. While one performs a task using the strategy (primary task), one may also monitor and evaluate how successful the strategy is (secondary task). When the strategy becomes less successful, one may attempt to develop an alternative strategy and evaluate its outcome. As workload from the primary task consumes more mental resources, fewer resources will be available for the secondary task interfering with the ability to adopt an alternative strategy. One can further question whether the type of workload would affect strategy use. In contrast to a single-resource view (Kahneman, 1973) that assumes a capacity-limited pool of undifferentiated resources that can be allocated to multiple activities, a multiple-resource view (Brooks, 1968; Navon & Gopher, 1979; Wickens, 2002) assumes that multiple capacity-limited pools of resources exist for different processes (e.g., perceptual, motor). The multiple-resource view predicts that two tasks that share the same resource structures will cause greater interference than two tasks that use different resource structures. Based on the multiple-resource view, we investigated the role of workload in strategy adoption by manipulating type of workload imposed on individuals performing a dynamic task. The significant relationship between working-memory capacity and strategy use (e.g., Beilock & DeCaro, 2007; Schunn & Reder, 1998) suggested manipulation of working-memory load. However, one can question whether it is the most relevant manipulation of workload in a complex dynamic task that requires a high level of perceptual-motor coordination. Therefore, in another condition we used a perceptual-motor load manipulation.

Substantial individual differences in reasoning and problem solving have challenged the development of a unified theory of strategy use (Roberts & Newton, 2001). The cognitive style account claims that different individuals have qualitatively distinct, consistent approaches to organizing and processing information. Cognitive styles reflect relatively fixed, stable cognitive structures that emerge as a function of genetic disposition, maturation, and experience (Kogan, 1980) and predispose individuals to particular preferences in instructional methods in learning situations (Riding & Sadler-Smith, 2002). Evidences suggest that matching the cognitive style with learning activity can optimize learning performance (Hayes & Allinson, 1993; Hayes & Allinson, 1996).

Individual differences in strategy use have been observed not only in academic learning situations (e.g., learning course materials, mathematical problem solving) but also in complex tasks performed in dynamic environments (Best et al., 1998; John & Lallement, 1997; Reder & Schunn, 1999). However, the cognitive style account has mostly focused on the former. One might question whether the cognitive style account can provide insights to understanding individual difference in the latter. In typical training situations in which an ideal strategy for normal situations is instructed to all trainees (e.g., pilots trained to use an exemplary navigation strategy), individuals may exhibit distinct patterns in precisely how they execute the instructed strategy. We questioned whether those patterns would predispose individuals to different strategies when they encounter non-normal situations. We suspected that those who adopt an alternative strategy in a non-normal situation would exhibit certain behavioral characteristics that distinguish them from those who continue with the instructed strategy.

To summarize, the current study aimed to investigate two factors that can affect strategy use in a dynamic task: 1) Workload imposed during the adaptation to a new environment, and 2) individual differences in the pattern of prior strategy execution. We trained participants to practice one strategy in a standard environment and then introduced changes that made executing the practiced strategy much more challenging. We imposed different types of workload on participants adapting to the changed environment. We identified two groups of individuals, those who continued with the learned strategy and those who adopted an alternative strategy. We further investigated the behavioral precursors of future strategy adoption. We used the Space Fortress game, a real-time dynamic task that simulates multitasking activities such as piloting an aircraft.

2. Navigation strategy in the Space Fortress task

2.1. The Space Fortress task

The Space Fortress game (Donchin, 1989) is a computer-based video game that requires flexible coordination of perceptual, cognitive, and motor components in a dynamic environment. The game was originally developed for the learning strategy program initiated by DARPA and has been used in skill acquisition studies to explore the effects of various training or instructional strategies on learning outcomes (Boot et al., 2010; Erickson et al., 2010; Fabiani, Buckley, Gratton, Coles, & Donchin, 1989; Frederiksen & White, 1989; Gopher, Weil, & Bareket, 1994; Ioerger, Sims, Volz, Workman, & Shebilske, 2003; Lee et al., 2012; Mane, Adams, & Donchin, 1989; Newell, Carlton, Fisher, & Rutter, 1989; Whetzel, Arthur, & Volz, 2008).

The game (Fig. 1) mainly consists of four tasks: navigation, a fortress task, a mine task, and a bonus collection task. The participant navigates the ship in a frictionless environment by rotating it left or right (using the A and D keys, respectively) or thrusting (using the W key) to accelerate it. The participant has to control the ship to fly within an area enclosed by two hexagons.

A fortress stationed in the smaller hexagon rotates like a turret, tracking the ship's trajectory and firing shells at the ship if it stays within one of the fortress sectors (fixed-size areas, each 10° surrounding the fortress) longer than 1 s. The participant has to shoot the fortress with a missile (using the space bar) at least ten times and then make a rapid double-shot to destroy it. Once it is destroyed, a new fortress becomes available after 1 s. To earn the most points, the participant has to destroy the fortress as many times as possible while avoiding the shells from the fortress.

Mines appear at random locations. A mine can be either a ‘friend’ or a ‘foe’. At the beginning of each game, the participant is shown three