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IFAC-PapersOnLine 49-32 (2016) 101–106

An Experimental Investigation on Human Spatial Control Skill Development ⋆

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Abstract: The advances of modern human-machine systems change the roles of humans and motivate us to promote our understanding of human functions in human-machine systems and their progress through development. This paper illustrates human spatial control skill development through a remote-control flight task, which involves agile system dynamics, multiple control inputs coordination, and long-duration repetitions. The results demonstrate that skill development is a nonlinear process that progresses from purely open-loop control, to the coordination of open-loop control and closed-loop modulations, and finally to the emergence of interaction patterns. The paper also discusses the specificity effect of practice and the transition to generalization through skill development. The techniques developed in this paper ensure the generality of the conclusions across tasks.

Keywords: Man/machine interaction, aircraft control, skill acquisition, skill development, behavior pattern

1. INTRODUCTION

Over the last century, modern machine systems have taken over a broad range of human functions, to alleviate human workload, enhance human safety, and enable explorations of environments unreachable to humans. At the same time, the trend in modern machine systems has changed the roles of humans in human-machine systems from manual, to augmented, and ultimately to supervisory functions (Mettler and Li (2014)). This progress strengthens human-machine interactions and heightens the requirement of human skills to collaborate with more complicated machine systems.

The training of professional human skills is usually time-consuming. For instance, the Federal Aviation Administration requires a minimum of 1,500 hours of total flight time for an airline transport pilot. Similarly, the American Board of Surgery requires five years of progressive residency for general surgery certification. The high time and financial expenses of training motivates the investigation of human control functions in human-machine systems and their progress through skill development.

Spatial control skills are an essential aspect of human activities in a variety of human-machine systems. They emphasize the joint interactions encompassing human cognitive, perceptual, and motor control processes. This paper investigates the development of human spatial control skills through a remote-control flight task. The research primarily underscores human skill development on the dimension of atomic behavior units, in terms of interaction pattern. The results show that the emergence of interaction patterns relies on the coordination of well-tuned open-loop plans and closed-loop modulation mechanisms.

⋆ This research work was enabled thanks to financial support from the National Science Foundation (Career Grant CMMI-1254906).

The paper is organized as follows. First, Section 2 briefly reviews human skill development research. Section 3 then describes the experimental setup and configuration of a remote-control flight task. Section 4 presents theoretical descriptions of skill development progress, followed by experiment results of human pilots and their implications of skill development in Section 5. Finally, Section 6 provides general conclusions.

2. RELATED WORK

Spatial control skill development has been studied in various areas, such as motor control science (Sosnik et al. (2004, 2009)), cognitive science (Vigorito and a.G. Barto (2010)), and sports (Ward and Williams (2003); Keetch et al. (2005); Mehdizadeh et al. (2015)).

Power law of practice is the best-known empirical theory of skill development. It suggests that performance time against number of practice exhibits a linear decrease in a log-log plot followed by an asymptotic approach to an "incompressible" lower bound (Crossman (1959); Newell (1991)). The power law theory implies a continuous and linear development of human skills.

However, from the perspective of ecological psychology (Gibson (1979)), humans are embedded in a rich perceptual-motor environment with multiple degrees of freedom, which results in skill development being a functional rather than a function. Shaw and Alley (1985) argued that skill development can be discontinuous or nonlinear because it is difficult to assure the continuity at all dimensions.

Moreover, Krendel and McRuer (1960), Salmoni (1989), Bainbridge (1989), and Dreyfus (2004) all proposed that skill development can be idealized as a progression of phases. Throughout these phases, humans enhance their

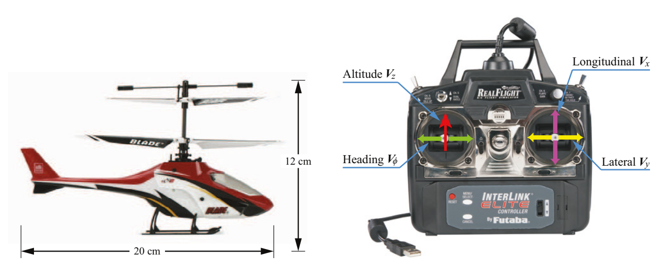
10.1016/j.ifacol.2016.12.197

skills by refining the identification of domain-specific features, the discrimination of situations, and the constructing and strengthening of situation-response mappings. These situation-response mappings, in the forms of motor programs (Keele (1968); Adams (1971); Schmidt (1975)), muscle synergies (Bernstein (1967)), interaction patterns (Kong and Mettler (2013); Mettler et al. (2015)), etc., represent functional elements that the central nervous system employs as the key organization principle for reducing structural and computational complexity.

In particular, motor programs are defined as the invariants generalized across a class of movements. Muscle synergies are defined as neural coordinative structures that activate multiple muscles with one neural command. The concept of interaction pattern extends muscle synergy by incorporating the perspective of ecological psychology that emphasizes human perception. The present research focuses on validating the emergence of interaction patterns during skill development.

3. EXPERIMENTAL SETUP AND HUMAN DATA

Human experiments were conducted in the Interactive Guidance and Control Lab (IGCL) at the University of Minnesota. (See Mettler et al. (2012b,a) for details.) The experiments use miniature rotor-crafts (e.g. Blade MCX2 in Fig. 1(a)) as test vehicles to exercise human pilots. These rotor-crafts are maneuvered with four control inputs: longitudinal and lateral cyclic to the lower rotor (denoted as control v_x and v_y), and collective and differential rotor rpm (denoted as altitude control v_z and heading control v_ϕ). Fig. 1(b) illustrates these four control inputs.



(a) Blade MCX2 (b) Flight Controller

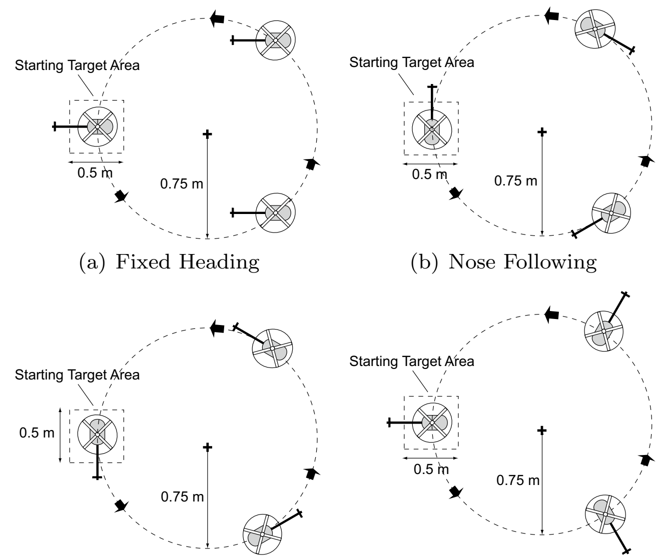
Fig. 1. Experimental facilities.

Experiment data was collected with four test pilots varying in years of experience and years holding a pilot license, as listed in Table 1. Due to the difficulty of tracking the development profile of a single pilot, this research uses these four pilots to represent different stages in the development process.

Table 1. Test pilots

Pilot	Pilot License	Years of Experience
1	Yes	2
2	No	1.5
3	Yes	0.5
4	No	0.2

We instructed these pilots to perform circle tracking tasks to maximize precision and minimize operation time, following four heading guidelines in Fig. 2. The radius of tracking reference is 0.75m, marked on the ground with eight stripe stickers. For each configuration, a pilot needs to complete three trials. Each trial lasts for around 2 minutes, consisting of 10 to 15 circles. All tasks are performed in a single day.



(a) Fixed Heading (b) Nose Following

(c) Tail Following (d) Pirouette

Fig. 2. Circle task configurations. Pilots are instructed to maneuver the micro-helicopter to track the circle following these four heading guidelines. The illustrations assume pilots track the circle in a counter-clockwise direction.

The circle tasks in this paper provide a more realistic process for studying human spatial control skills development. First, repetitions enable human performance stabilization. Early studies have also investigated repeated tasks, but they primarily focused on transient motions within 3 seconds. The control patterns in these motions, as Schmidt (1975) indicated in the schema theory, are essentially open-loop and ballistic, relying on knowledge of results (KR) to correct following trials. The circle tasks in this paper involve longer repetitive sessions and agile system dynamics, demanding real-time modulations.

Moreover, accomplishing the circle tasks requires coordinations of multiple control commands, compared with single-degree-of-freedom tasks in early studies. The optimal control profiles of these circle tasks can be easily derived, as listed in Table 2. They ensure all human pilots perform the planning function at the same level and emphasize behavior pattern emergence.

Table 2. Optimal control profiles of circle tasks

Task Setup	Optimal Control Profile
Fixed Heading	(collective) sinusoid x and y control
Nose Following	constant x and heading control
Tail Following	constant x and heading control
Pirouette	constant y and heading control

The lab uses 6 Vicon cameras to track the position and orientation of the helicopter in control at a sampling frequency of 100Hz. Fig. 3 presents the helicopter trajectories under the maneuver of the four pilots in the nose following configuration.