The Education of Attention as Explanation of Variability of Practice Effects: Learning the Final Approach Phase in a Flight Simulator

Michaël Huet
Université de la Méditerranée et CNRS

Cyril Camachon
Université de la Méditerranée et CNRS and Centre de Recherche de l’Armée de l’Air, Salon de Provence

Rob Gray
University of Birmingham

Gilles Montagne
Université de la Méditerranée et CNRS

David M. Jacobs
Universidad Autónoma de Madrid

Olivier Missenard
Université de la Méditerranée et CNRS

The present study reports two experiments in which a total of 20 participants without prior flight experience practiced the final approach phase in a fixed-base simulator. All participants received self-controlled concurrent feedback during 180 practice trials. Experiment 1 shows that participants learn more quickly under variable practice conditions than under constant practice conditions. This finding is attributed to the education of attention to the more useful informational variables: Variability of practice reduces the usefulness of initially used informational variables, which leads to a quicker change in variable use, and hence to a larger improvement in performance. In the practice phase of Experiment 2 variability was selectively applied to some experimental factors but not to others. Participants tended to converge toward the variables that were useful in the specific conditions that they encountered during practice. This indicates that an explanation for variability of practice effects in terms of the education of attention is a useful alternative to traditional explanations based on the notion of the generalized motor program and to explanations based on the notions of noise and local minima.

Keywords: concurrent feedback, information, landing, noise, self-controlled feedback

Many actions require high levels of perceptual-motor skill. An example of an action that requires a high level of skill is landing an aircraft. Three subtasks are performed during the landing phase: first, the base to final turn consists of aligning the aircraft with the runway (Beal & Loomis, 1997); second, in the final approach phase, the pilot gradually decreases speed and altitude through a stable descent (Lintern, 2000); finally, just before ground contact, the aircraft is tilted slightly nose-upward, a maneuver called the landing flare (Palmisano, Favelle, & Sachtler, 2008). Visual landings are landings without use of on-board instruments. These landings are generally considered the most challenging phase of normal flights (Langewiesche, 1944). In this study we focus on the final approach phase of visual landings.

In the final approach phase the pilot aims to fly within the glide slope area. This area consists of a virtual cone whose origin is located at the aiming point on the runway. The cone is bounded by a lower limit, generally an approach angle of 2.8°, and an upper limit, generally an approach angle of 3.2°. If the trajectory of the aircraft is too low, collisions may occur with obstacles such as buildings, trees, or antenna towers. On the other hand, the risks of too high trajectories include overrunning the end of the runway and hard landings (Benbassat & Abramson, 2002). The final approach phase can be especially difficult for novice pilots when they land an aircraft at an airport they have not experienced previously. Several visual cues (runway shape, landmarks on the ground) are different at different airports, sometimes leading pilots to misjudge altitude or approach angle (Mertens, 1981; Mertens & Lewis, 1982). Facilitating the learning of this phase is therefore an important challenge.

To address this challenge we consider the variability of practice hypothesis (Schmidt, 1975). The variability of practice hypothesis holds that performance improves more with variable practice than...
with constant practice. Many studies have reported or reviewed empirical evidence related to the hypothesis (e.g., Buekers, 1995; Shea & Wulf, 2005; van Rossum, 1990; see also Schöllhorn, 2000; Schöllhorn et al., 2006; Shea & Morgan, 1979, for related work). Buekers, for example, compared the performance of two groups that practiced basketball shots. The first group performed shots from different distances (variable practice), whereas the second group performed shots from a single distance (constant practice). The two groups performed a transfer test from a new distance. The constant group performed better than the variable group during the acquisition phase. In contrast, the variable group performed better than the constant group in the transfer test.

The empirical work concerning variability of practice originated as a test of Schmidt’s (1975) schema theory, which provides an explanation of the beneficial effect of variability. The key concept of this theory is the Generalized Motor Program (GMP). A single GMP is hypothesized to control a class of actions with a similar overall structure (e.g., writing one’s signature, performing a basketball shot). To apply a GMP to the control of a particular action in the class, several parameters have to be set that control more detailed aspects of the action (e.g., speed, amplitude). In this theoretical framework, learning consists of acquiring knowledge about the relation between parameters of the GMP and movement outcomes. Variable practice is hypothesized to be effective because it allows the learner to sample a useful range of parameter-set/movement-outcome pairs. Constant practice, in contrast, is hypothesized to be less effective because it repeatedly provides the learner with the same parameter-set/movement-outcome pair, or with similar ones, which does not help the learner as much in discovering the relation between parameters and movement outcomes.

The present study is motivated by an alternative explanation of the beneficial effects of practice variability. Ecological theorists claim that perceptual-motor learning involves a change in the informational basis of an action: With practice, learners come to rely on more useful informational variables (e.g., Michaels & de Vries, 1998). This process is referred to as the education of attention (Gibson, 1979). Imagine that an observer uses an informational variable that, under normal circumstances, is not among the more useful ones. Practice conditions can be designed to enhance or reduce the usefulness of the used variable. Changes in variable use, then, occur more slowly if the initially used informational variable is highly useful during practice, and more quickly if the initially used variable is less useful during practice (Fajen & Devaney, 2006; Jacobs, Runeson, & Michaels, 2001). This means that to design optimal practice conditions one should reduce the usefulness of initially used informational variables. Our hypothesis is that practice conditions with high variability are effective to the extent that the initially used informational variables are less useful in such practice conditions. To illustrate this hypothesis and apply it to the case of landing we need to discuss the informational variables that are available during landing.

A first candidate variable is the visual angle between the horizon and the aiming point, as seen from the aircraft. Lintern and Liu (1991) reported experimental results that are consistent with the use of this variable, which they referred to as absolute H angle (cf. Langewiesche, 1944). Under normal circumstances the absolute H angle specifies approach angle: It remains constant when the approach angle remains constant and it changes when the approach angle changes. This specifying relation is independent of, say, texture density, runway width, and the pilot’s eye position in the cockpit; the absolute H angle is not affected by variability in such factors. Galanis, Jennings, and Beckett (1998) also described the relative H angle, which refers to the visual angle between the aiming point and an arbitrary point on the aircraft. For approaches with a given pitch angle, the relative H angle specifies approach angle if the eye position of the pilot stays constant with respect to the cockpit. Variability in eye position, however, affects the relative H angle, and thereby breaks the specificity between the relative H angle and approach angle.

Another type of information is the form ratio of the runway, defined as the optical length of the runway divided by the optical width. Experiments conducted by Mertens (1981) and Mertens and Lewis (1982) indicate that the form ratio is indeed relevant to the performance of pilots in the approach phase. This variable specifies approach angle in situations in which all used runways have the same physical length-over-width ratio. This is the case, for instance, if a pilot always lands on the same runway. The form ratio is affected by trial-to-trial variability in the physical shape of the runway: The use of this variable predicts pilots to fly lower in approaches to narrow runways as compared to wide runways. The use of the form ratio can hence lead to dangerous situations especially for pilots who occasionally land on narrow runways while they are used to landing, or trained to land, on wider runways.

Also of interest is the visible texture of the ground surface. Texture density has been shown to affect the accuracy of visually guided approaches (Lintern, 2000; Lintern & Walker, 1991). Approaches are less accurate if performed in scenes with less texture (cf. Lintern & Liu, 1991). Numerous higher-order and lower-order variables have been identified in relation to the visible texture. Among these variables are gradients and perspective angles (Flach, Warren, Garness, Kelly, & Standard, 1997; Lintern, 2000) and higher-order properties of the optic flow field (Gibson, Olum, & Rosenblatt, 1955). The use of texture-related information by pilots under normal circumstances is also evidenced by black hole accidents, which are accidents that occur in the absence of a distinguishable ground texture (Gibb, 2007; Gibb, Schwaneveldt, & Gray, 2008).

In addition to the possible use of one of the previously described variables, we consider the possibility that performance is affected by compound variables that are defined with combinations of variables. To do so we compare the empirical results of Experiment 2 to the predictions of a quantitative model. The model predicts flight trajectories on the basis of the compound variables. These analyses apply aspects of the theory of direct learning (Jacobs & Michaels, 2007): The candidate variables are described as points in a state space, referred to as information space, and changes in variable use are portrayed as a movement in the information space. Even so, the results of the present experiments can equally well be interpreted from, and have similar implications

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1 The approach angle is defined as the angle between the horizontal and the imaginary line from the aircraft to the aiming point.
for, related approaches such as Brunswikian, Bayesian, and other cue-combination approaches.2

In summary, the capacity to detect and correctly use sufficiently useful sources of information is of crucial importance for visual landings. Given that novices do not always use optimal informational variables, this skill has to be learned. Huet, Jacobs, Camachon, Goulon, and Montagne (2009) reported that participants who performed the approach phase in a flight simulator improved substantially after 180 practice trials. This improvement was attributed to changes in variable use. In that study we were interested in the type of feedback that leads to the quickest improvement in performance. It was shown that concurrent feedback provided with a self-controlled schedule (i.e., with learners controlling when they receive the feedback; cf. Huet, Camachon, Fernandez, Jacobs, & Montagne, 2009) is more beneficial than concurrent feedback provided with an imposed schedule (i.e., with learners receiving the feedback at predetermined moments), which, in turn, is more beneficial than practice without concurrent feedback.

In the present study we use the type of feedback that was found to be most beneficial by Huet, Jacobs et al. (2009)—self-controlled concurrent feedback—and address the effects of practice variability. In Experiment 1, two groups of participants (constant and variable groups) practiced the landing task on four consecutive days, with a simulator, under constant or variable practice conditions. In the practice phases of Experiment 2 one of three experimental factors was held constant, and variability was applied to the remaining two factors. In the General Discussion alternative interpretations of our results are addressed, including the specificity of practice hypothesis (Proteau, 1992) and a dynamical systems explanation in terms of noise and local minima (Schöllhorn, Mayer-Kress, Newell, & Michelbrink, 2009).

Experiment 1

In this experiment we applied the variability of practice methodology to the final approach phase in landing. We contrasted performance of constant and variable practice groups. In variable practice, trial-to-trial variability was applied to three factors: texture density, runway width, and the eye height of the participant in the cockpit. We hypothesized that the variable group would outperform the constant group in a transfer test performed with new values of the three factors. This would be in agreement with previous research concerning variability of practice.

Method

Participants. Ten students and faculty members (mean age = 27.5, SD = 3.17) participated in the experiment. All of them had normal or corrected-to-normal vision. They were randomly assigned to one of the two groups. Participants had no prior flight experience and were not informed about the purpose of the study.

Task. We used the same simulated flight task as in Huet, Jacobs et al. (2009). Participants approached the runway in a Cessna 172, trying to stay within the glide slope area. The control of the aircraft was visual (i.e., without on-board information displays). This task is of primary interest because it requires constant regulation: The purpose of the final approach phase is not only to be well placed at the end of the maneuver but to follow the glide slope area all along the maneuver. At the beginning of each trial the aircraft was located at a distance of 2,700 m (1.46 Nm) from the landing point, at an altitude randomly chosen from 15 equidistant values between 107 and 126 m (353 and 416 ft). This meant that the aircraft always started below the glide slope area. The initial speed was 42.18 m/s (82 knots). The trials started with a countdown of 3 s during which the autopilot was enabled. For the rest of the trial participants controlled the altitude of the aircraft by pushing a joystick forward or backward. The lateral position of the aircraft remained aligned with the center of the runway. To focus exclusively on the final approach phase the trials ended 500 m before the landing point, well before the initiation of the landing flare. The trial duration was about 50 s.

Concurrent and terminal feedback was provided to all participants (cf. Huet, Jacobs, et al., 2009). The concurrent feedback was in the form of a Precision Approach Path Indicator (PAPI). The PAPI was located at the left side of the runway, as seen from the aircraft, close to the aiming point. A PAPI consists of four lights whose colors (red or white) indicate the aircraft’s Current Glide Slope (CGS). Two red and two white lights indicate that the aircraft is located within the glide slope area (2.8° < CGS < 3.2°), three or four red lights indicate that the aircraft is below this area (2.5° < CGS < 2.8° or CGS < 2.5°, respectively), and three or four white lights indicate that the aircraft is above the area (3.2° < CGS < 3.6° or 3.5° < CGS). The concurrent feedback was provided in a self-controlled manner (Chiviacowski & Wulf, 2002; Huet, Camachon, et al., 2009): When a participant pressed a button on the joystick a PAPI appeared for 2 s and then disappeared automatically. In addition, terminal feedback was given after each practice trial. This feedback showed the aircraft’s trajectory on the trial together with the glide slope area in a 2-D side view.

Apparatus. Figure 1 illustrates the set-up: an aviation-game joystick (Saitek AV8R), a large projection screen, a Barco-Projector, and a PC (Dell Precision 380). Participants sat at a distance of 1.2 m from the screen, which had an angular size of 102 × 87 degrees (horizontally × vertically). The data from the joystick were sampled at a frequency of 100 Hz. The PC used these data to calculate the updated position of the aircraft in the virtual environment; the updated visual scene was projected on the screen with a delay of less than 50 ms. The visual scene was changed at a rate of 60 frames/s.

2 Cue-combination approaches hold that, to detect compound variables, observers first detect the component variables and then combine these variables through hypothetical cognitive combination processes. Information-space-based approaches are related to the direct-perception view in the sense that no assumptions are made about how compound variables are detected, meaning that fine-grained detail at the level of detection processes is considered as being beyond the scope of the analysis. In other words, in information-space-based approaches variables described as combinations of other variables have the same ontological status as variables not described as combinations (Jacobs & Michaels, 2007). We refer the reader to Michaels and Isenhower (2011a) for a comparison of approaches based on the notion of information space to cue-combination approaches (cf. Arzamaszki, Isenhower, Kay, Turvey, & Michaels, 2010; Kirlik, 2009).
The flight kinematics of the aircraft in the virtual environment were computed using the JSBSim open-source flight-dynamics model (Berndt, 2004). The virtual runway, ground surface, and cockpit were produced with I.C.E. (Imagine, Create, Experiment), a software package developed at the Institute of Movement Sciences, Marseille (cf. Bastin, Craig, & Montagne, 2006; Huet, Camachon, et al., 2009). The runway was 1,200 m long and 30 m wide, meaning that it had a length-over-width ratio of 40. The runway was gray and the rest of the environment consisted of filled black circles with a diameter of 13 m on a yellow ground surface. We used black circles because this allowed us to easily manipulate the texture density.

**Procedure.** The experiment consisted of a calibration period, pretest, acquisition phase, retention test, and transfer test. The calibration period consisted of 15 trials during which the participant flew through large rings located at different altitudes. The rings had a diameter of 15 m and were located at altitudes between 190 and 280 m. This exercise familiarized participants with the flight simulator. Then, before the pretest, instructions about the experimental task were given and a video of a typical approach was shown. The video was shown to ensure that participants understood the task. The pretest consisted of 15 trials without concurrent feedback and without terminal feedback. The acquisition phase consisted of 180 trials: three blocks of 15 trials per day during a 4-day period. An additional block of 5 trials without concurrent feedback and without terminal feedback was performed at the end of each daily session; these no-feedback blocks were included to assess the participants’ level of performance during the acquisition phase. The day after the last day of acquisition a 15-trial retention test and a 10-trial transfer test without feedback were run. The retention test was identical to the pretest. Only 10 trials were used in the transfer tests to prevent adaptation to the test conditions. The phases of the experiments are summarized in Table 1.

**Experimental groups.** There were two experimental groups: variable and constant. The 15-trial acquisition blocks were different for these groups. For the variable group, the simulated conditions were changed from trial to trial. The changes were applied to three factors: texture density, runway width, and eye height. Fifteen equidistant values were used for each experimental factor. The boundary values were 165 and 1,005 points/km² for texture density, 19 and 57 m for runway width, and −5.25 and 5.5 cm for the pilot’s eye height. The values for eye height are given relative to the pilot’s usual eye position, which is 32 cm above, 36 cm in front of, and 21 cm to the left of the center of mass of the aircraft. For the variable group one of the 15 values of each factor was randomly assigned to each practice trial. For the constant group the values of the experimental factors were the same on each trial: 555 points/km² for texture density, 28.6 m for runway width, and 0 cm for eye position (i.e., the eye position was the pilot’s usual one). The values of these factors that were used in the pretest, the additional 5-trial blocks in the acquisition phase, and the retention test were identical to the ones used for constant practice. The transfer test was performed with values of the experimental factors that were new for both groups: The pilot’s eye height was fixed at 8 cm above its usual position, the runway had a width of 13 m (i.e., a length-over-width ratio of 92), and the texture density was 40 points/km².

**Dependent variables.** We used data obtained between 2,500 and 500 m before the landing point. The variable *time flown within the glide slope area* was calculated as the percentage of time that the virtual aircraft was located within the glide slope area with respect to the total time of the trials. The self-controlled feedback data were analyzed through the frequency of requests, which is the number of times that a participant pressed the button on the joystick to obtain the concurrent feedback. The frequency of the requests was calculated for each day of the acquisition phase and for each participant.

![Figure 1. Apparatus used in the experiments, including a joystick, a video projector, a large screen, and a control station.](image-url)
Results

Percentage of time in glide slope area. Figure 2 shows the average percentage of time flown within the glide slope area for the two experimental groups in the pretest, acquisition phase, retention test, and transfer test.

Pretest. A one-way ANOVA on the percentage of time within the area did not reveal a significant effect of experimental group, $F(1, 8) = 0.41, p > .05$.

Acquisition phase. A two-way ANOVA with Day (Days 1 to 4) as within-subjects factor and Group (constant, variable) as between-subjects factor was performed on the percentage of time within the area in the additional 5-trial acquisition blocks without feedback. The only significant effect was the effect of Day, $F(3, 24) = 4.68, p < .05, \eta^2_p = 0.37$. A posteriori comparisons (Newman–Keuls) indicated that performance increased for both groups: Significant differences were observed between Day 1 and Day 4 and between Day 2 and Day 4 ($p < .05$).

Retention test. A two-way ANOVA with Group (constant, variable) as between-subjects factor and Test Phase (pretest, retention test) as within-subjects factor was performed. A significant effect was observed for Test Phase, $F(1, 8) = 46.41, p < .05, \eta^2_p = 0.85$. A posteriori comparisons (Newman–Keuls) revealed an increase in performance from pretest to retention test for both groups ($p < .05$).

Transfer test. A two-way ANOVA with Group (constant, variable) as between-subjects factor and Test Phase (retention test, transfer test) as within-subjects factor was performed with percentage of time within the glide slope area as dependent measure. The analysis revealed a significant effect for Test Phase, $F(1, 8) = 38.67, p < .05, \eta^2_p = 0.82$, and for the Test Phase × Group interaction, $F(1, 8) = 5.76, p < .05, \eta^2_p = 0.42$. A posteriori comparisons (Newman–Keuls) revealed a decrease in performance from retention test to transfer test for both groups ($p < .05$). Furthermore, in the transfer test the variable group performed better than the constant group ($p < .05$).

Frequency of feedback requests. Figure 3 presents the frequency of requests for each participant in the constant group (left panel) and variable group (right panel). A qualitative inspection of the figure does not show a substantial reduction in the amount of requests across the acquisition phase. Participants did show individual differences in the use of the feedback. For instance, in the constant group, Participant 3 (filled triangles) frequently asked for feedback throughout the acquisition phase and Participant 5 (filled squares) decreased the number of requests from Day 1 to Day 2.

Discussion

Our goal in Experiment 1 was to determine whether variability of practice facilitates the final approach phase in landing. As in classical variability of practice experiments, participants practiced under variable or constant conditions. The variable group outperformed the constant group in the transfer test. This is consistent with previous findings (e.g., Buekers, 1995; Shea

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<th>Experimental Phases in Experiments 1 and 2</th>
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<td>Day 1</td>
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<td>Calibration period</td>
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<td>Pretest</td>
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<td>Note: All blocks consist of 15 trials, unless stated otherwise. a Used in Experiment 2; Experiment 1 included only a single transfer test.</td>
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A possible explanation of this result is the following: Variable practice leads to a quicker change in variable use, and hence to a larger improvement in performance, because it reduces the usefulness of initially used informational variables. Experiment 2 further explores this interpretation.

The finding that self-controlled feedback schedules lead to substantial individual differences in the feedback requests is also consistent with previous studies (Chiviacowski & Wulf, 2002; Huet, Camachon, et al., 2009; Huet, Jacobs, et al., 2009). In these studies it was argued that such individual differences are indicative of why self-controlled schedules are beneficial: Self-controlled schedules allow learners to ask for the feedback and hence to receive the feedback at moments that suit their individual needs.

**Experiment 2**

This experiment further explores variability of practice effects in the learning of the final approach phase. Participants in a first practice condition, the fixed cockpit condition, practiced with a constant eye height in the cockpit and with trial-to-trial variability applied to texture density and runway width. Participants in a second condition, the fixed runway condition, practiced with a constant runway width and with variability applied to texture density and eye height. A first transfer test was performed under the conditions of the fixed runway practice and a second one under the conditions of the fixed cockpit practice. We hypothesized that the fixed cockpit group would maintain a high level of performance in the fixed-cockpit transfer test and have a decreased level of performance in the fixed-runway transfer test. The opposite profile of results was predicted for the fixed runway group. In addition, the variability in the transfer tests of this experiment allowed us to fit a quantitative model, and hence to further explore the claim that variability of practice effects are related to the education of attention and to the usefulness of informational variables during practice.

**Method**

**Participants.** Ten students and faculty members (mean age = 28.1, SD = 2.92) participated in the experiment. All of them had normal or corrected-to-normal vision. They were divided into two groups of equal size (n = 5). Participants had no prior flight experience and they were not informed about the purpose of the study. None of them participated in Experiment 1.

**Experimental groups.** The two groups were: the fixed cockpit group and the fixed runway group. The acquisition phase was organized differently for these groups. For the fixed cockpit group, trial-to-trial changes were applied to texture density and runway width, but eye height was held constant. For the fixed runway group, trial-to-trial changes were applied to texture density and eye height, but runway width was held constant. The individual experimental factors were varied as in the variable practice condition of Experiment 1. The values of the factors that were not varied were as in the constant practice of that experiment.

**Task, apparatus, procedure, and dependent variables.** The task, apparatus, and procedure were as in Experiment 1, with exception that two transfer tests were used instead of one. A first transfer test was performed with fixed runway conditions and a second transfer test with fixed cockpit conditions. The transfer tests consisted of 10 trials. The order of the transfer tests was counterbalanced among participants. We computed the same dependent variables as in Experiment 1: percentage of time in glide slope area and frequency of feedback requests. In addition we calculated the vertical distance between the aircraft’s position and the bisecting line of the glide slope area (3°). This variable is called altitude deviation (Gibb et al., 2008).

**Quantitative model predictions.** To analyze the informational variables used after practice we compared the 20 flight trajectories observed for each participant during the transfer tests to flight trajectories predicted by a model. Let us mention that this type of analysis cannot be applied to the pretest and retention test, and neither to the test phases of Experiment 1, because it requires variability in the experimental factors. For these analyses we used data observed between 2,000 and 500 m before the landing point. The model predictions were computed as follows.

For each participant we first computed the relative $H$ angle that best predicted his or her flight trajectories, assuming that the participant controlled the aircraft so as to maintain the relative $H$ angle constant. To do so we started with 50 equidistant relative $H$ angles in a range from 4.5 to 6.1°. For each of these 50 values we computed the 20 approach trajectories (one for each transfer trial) for which the $H$ angle had that particular value at each point of the
We then computed which of the 50 sets of relative-$H$-angle predictions led to the lowest absolute altitude deviation between the predicted and observed trajectories. We use the notation $H_n(d)$ to refer to the flight altitude predicted on trial $n$, at distance $d$ from the landing point, by the relative $H$ angle that led to the best-fitting predictions for the considered participant.

In a similar way we computed, for each participant, the form ratio that best predicted the 20 trajectories observed in the transfer tests. Again, this means that we first computed the approach trajectories from which the runway is seen as having a particular optical length-over-width ratio, for each ratio in a range from 1.42 to 1.98 (in 50 equidistant steps), and then determined for which of the form ratios the computed trajectories best fitted the trajectories that were observed for the participant. We use the notation $R_n(d)$ to refer to the flight altitude predicted on trial $n$, at distance $d$ from the landing point, by the best-predicting form ratio. For example, if $R_n(1000) = 102$ for a particular participant, then the best-fitting form ratio predicts that the flight altitude of that participant on the third transfer trial, at 1,900 m before the landing point, is 102 m.

If a participant primarily used relative $H$ angle to control altitude (i.e., if he or she flew so as to keep the relative $H$ angle constant), then the $H_n(d)$ predictions should provide a good fit to the observed trajectories. In contrast, if a participant used the form ratio to regulate altitude, then the $R_n(d)$ predictions should provide better fits. More interestingly, it is also possible that observers relied on combinations of these two variables or on higher-order compound variables that can be described as such combinations. To address this possibility we computed compound predictions, $C$, according to the formula:

$$C_n(d) = w \times H_n(d) + (1-w) \times R_n(d),$$

where $w$ is a weight parameter that ranges between 0 and 1. For each participant we used the predictions $H_n(d)$ and $R_n(d)$, computed as described above, to determine the value of $w$ for which the predictions $C_n(d)$ showed the best fit to the observed trajectories. In other words, for each participant we computed the value of $w$ for which the observed trajectories showed the lowest absolute altitude deviation with respect to the predictions $C_n(d)$. Best-fitting $w$ values that are close to 0 can be interpreted as evidence for the use of an informational variable that is more similar to the form ratio than to the relative $H$ angle, and vice versa for $w$ values that are close to 1.

### Results

This section presents (1) ANOVAs on the percentage of time in the glide slope area, (2) a qualitative inspection of individual flight trajectories, (3) the quantitative modeling efforts, and (4) an analysis of the feedback requests.

#### Percentage of time in glide slope area

Figure 4 shows the time in the glide slope area observed in Experiment 2.

**Pretest.** A one-way ANOVA on the percentage of time within the glide slope area did not reveal a significant effect of experimental group, $F(1, 8) = 0.003$, $p > .05$.

**Acquisition phase.** A two-way ANOVA with Day (Days 1 to 4) as within-subjects factor and Group (fixed cockpit, fixed runway) as between-subjects factor was performed on the percentage of time within the area in the 15-trial acquisition blocks in which concurrent feedback was given (not shown in Figure 4). This analysis revealed a significant effect of Day, $F(3, 24) = 7.32$, $p < .05$, $\eta^2_g = 0.47$. A posteriori comparisons (Newman–Keuls) indicated that performance increased significantly from Day 1 to all other days ($p < .05$), for both groups. Analyses that used data from the additional blocks of 5 trials without concurrent and terminal feedback (shown in Figure 4) did not reveal significant effects ($p > .05$).

**Retention test.** A two-way ANOVA with Group (fixed cockpit, fixed runway) as between-subjects factor and Test Phase (prettest, retention test) as within-subjects factor was performed, again with percentage of time within the glide slope area as dependent measure. A significant effect was observed for Test Phase, $F(1, 8) = 16.95$, $p < .05$, $\eta^2_g = 0.67$. A posteriori comparisons (Newman–Keuls) revealed an increase in performance from pretest to retention test for both groups ($p < .05$). Note that no significant group differences were observed in this analysis.

**Transfer tests.** A two-way ANOVA with Group (fixed cockpit, fixed runway) as between-subjects factor and Test Phase (retention test, fixed cockpit transfer, and fixed runway transfer) as within-subjects factor was performed with percentage of time within the glide slope area as dependent measure. The analysis revealed significant effects of Test Phase, $F(2, 16) = 16.17$, $p < .05$, $\eta^2_g = 0.67$, and Test Phase by Group, $F(2, 16) = 16.10$, $p < .05$, $\eta^2_g = 0.66$. A posteriori comparisons (Newman–Keuls) revealed that the fixed runway group performed better in the retention test and in the fixed-runway transfer test than in the fixed-cockpit transfer test ($p < .05$). The performance of the fixed runway group was not found to differ between the retention test and the fixed-runway transfer test. The profile of results was reversed for the fixed cockpit group: A posteriori comparisons did not reveal a difference between the retention test and the fixed-cockpit transfer test.

#### Used informational variables: qualitative inspection of trajectories

The previous subsection showed that the fixed cockpit and fixed runway groups came to perform differently in the transfer tests. In our interpretation this is at least partly because the different types of variability led participants to converge toward different informational variables. The following subsections address evidence related to the use of informational variables.

**Fixed cockpit participant.** Figure 5 presents the time evolution of the altitude deviations of a representative participant in the fixed cockpit group, for two trials in the fixed-runway transfer test (left panel) and two trials in the fixed-cockpit transfer test (right panel). The trials used in the fixed-runway transfer test are the ones with the highest and lowest eye heights. The participant flew

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1. To compute the predicted trajectories one needs to know the pitch of the aircraft, because the pitch affects the relative $H$ angle. We assumed the pitch to be constant throughout each approach. The constant pitch used for a particular trial was the average pitch observed for all trials with the same eye height. To compute the trajectories one also needs to know the visible reference point on the aircraft with regard to which the relative $H$ angle is defined. We estimated this point to be 1.80 m in front of, 21 cm to the left, and 1 cm below the center of mass of the aircraft (defined for aircraft in horizontal position).

2. Used informational variables: qualitative inspection of trajectories. The previous subsection showed that the fixed cockpit and fixed runway groups came to perform differently in the transfer tests. In our interpretation this is at least partly because the different types of variability led participants to converge toward different informational variables. The following subsections address evidence related to the use of informational variables.

3. Fixed cockpit participant. Figure 5 presents the time evolution of the altitude deviations of a representative participant in the fixed cockpit group, for two trials in the fixed-runway transfer test (left panel) and two trials in the fixed-cockpit transfer test (right panel). The trials used in the fixed-runway transfer test are the ones with the highest and lowest eye heights. The participant flew...
higher with the highest eye height (continuous curve) than with the lowest eye height (dashed curve). For higher eye heights one needs to fly higher to obtain the same relative $H$ angle. The altitude differences shown in the left panel of the figure are therefore in agreement with reliance on the relative $H$ angle. The trials presented for the fixed-cockpit transfer test are the ones with the widest runway (continuous curve) and narrowest runways (dashed curve). A less pronounced altitude difference is observed for these trials. This seems to indicate that the participant relied less on the form ratio than on the relative $H$ angle.

**Fixed runway participant.** Figure 6 presents analogous data for a participant in the fixed runway group. The manipulations of eye height (left panel) had a distinguishable effect on the altitude of the trajectories: The participant flew higher with the highest eye height (continuous curve) than with the lowest eye height (dashed curve). This effect is as predicted by the use of relative $H$ angle. Note, however, that the effect is less pronounced in Figure 6 than for the fixed cockpit participant shown in Figure 5. The curves in the right panel both lie below the glide slope area, but they are fairly similar and hence do not provide evidence for the use of form ratio. One might tentatively interpret these findings as indicating that the performance of this participant was more affected by relative $H$ angle than by form ratio, but that the reliance on relative $H$ angle was less pronounced for this participant than for the fixed cockpit participant. We next aim to confirm these qualitative observations with quantitative analyses.

**Used informational variables: quantitative modeling results.** Table 2 presents results of the quantitative model. First note that the altitude deviations, or fits, are lower for relative $H$ angle than for form ratio. This means that the predictions based on relative $H$ angle better approximate the observed trajectories than the predictions based on form ratio. Our main interest, however, is in the $w$
values in the table. The trajectories predicted by the variable form ratio are associated to the value \( w / H_{110050} \) and those predicted by relative \( H \) angle to \( w = 1 \). Other \( w \) values represent compound variables, or combinations of the predictions for relative \( H \) angle and form ratio (see Equation 1 above). For example, the trajectories of Participant 1 are best characterized by \( w = .91 \), meaning that the compound variable used by this participant places more weight on relative \( H \) angle than on form ratio.

The parameter \( w \) can be interpreted as the coordinate of a one-dimensional space (cf. Jacobs & Michaels, 2007; Michaels & Isenhower, 2011b). The left panel of Figure 7 presents this space together with Gaussian distribution functions. The peaks of the Gaussian curves are located at the group means of the \( w \) values and the widths of the curves are related to the within-group variance in the \( w \) values. The curves can be interpreted as follows: The higher the curve is for a particular group and above a particular point, the more likely it is that an individual in that group uses the compound variable represented by that point. The dashed curve lies further to the right than the continuous one, which is to say, closer to \( w = 1 \), or relative \( H \) angle. A \( t \) test for independent samples showed that the difference in the \( w \) values of the two experimental groups was significant (\( p < .05 \), single-tailed). This indicates that participants in the fixed cockpit group were more likely to use compound variables similar to relative \( H \) angle.

The right panel of Figure 7 gives the percentage of white-white-red-red PAPI feedback that a participant would receive during fixed runway practice (continuous curve) and fixed cockpit practice (dashed curve) if he or she controlled the aircraft using the informational variables represented by the points on the horizontal axis. The numerical simulations used to obtain these percentages assumed that the participant asks for feedback at randomly chosen moments, and that his or her altitude randomly fluctuates in a range from 10% below to 10% above the trajectories predicted by the \( w \) value. Furthermore, the predicted trajectories used in the simulations were based on a close to optimal calibration (i.e., value at which the informational variables are held constant). The curves in the right panel of the figure can be interpreted as usefulness curves. The use of variables similar to form ratio (low \( w \) values) would lead to a higher percentage of satisfactory feedback than the use of variables similar to relative \( H \) angle (high \( w \) values) in the fixed runway practice (continuous curve), and vice versa for the fixed cockpit practice (dashed curve). In other words, the fixed runway practice reduced the usefulness of the variables on the right side of the space (e.g., relative \( H \) angle) whereas the fixed cockpit practice reduced the usefulness of the variables on the left side of the space (e.g., form ratio).

The difference between the continuous and dashed curves in the right panel of Figure 7 is interesting for the following reason. Assume that the pretraining performance of participants can be characterized by a single distribution function that lies somewhere between the postpractice ones shown in the left panel of the figure. Also assume that, during practice, participants slowly change in variable use, or move through the space, so as to optimize the amount of satisfactory feedback that they receive. Given the usefulness curves in the right panel of the figure, this would mean that fixed runway participants would move to the left during the acquisition phase, and fixed cockpit participants to the right. Hence, taken together, these assumptions would explain the post-

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**Figure 6.** Altitude deviations for two trials in the fixed-runway transfer test (left panel) and fixed-cockpit transfer test (right panel), for a representative participant in the fixed runway group of Experiment 2. The presented trials are the ones with the highest and lowest eye height (left panel) and with the widest and narrowest runways (right panel). The area between the dotted lines represents the glide slope area.
practical difference in variable use shown in the left panel of the figure. To anticipate the General Discussion, it might be useful at this point to note that the previous reasoning assumes the usefulness curves to be the inverse of the potential function of the learning process.

Frequency of feedback requests. Figure 8 presents the frequency of requests for the fixed cockpit group (left panel) and the fixed runway group (right panel). The frequency presents data for the entire acquisition phase for each participant. The figure shows a substantial reduction in the amount of requests across the experiment only for Participants 5 and 9. The figure also shows a high level of interparticipant variability in the use of the feedback, as was the case in Experiment 1.

Discussion

Experiment 2 compared the effects of two practice conditions: fixed cockpit and fixed runway practice. No significant group differences were observed in the pretest, practice, and retention test. As hypothesized, participants maintained a high level of performance in the transfer test with the same variability conditions as the ones that they encountered in practice, but not in the other transfer test. Significant postpractice group differences in variable use were observed. After practice participants were less likely to use variables whose usefulness was reduced in the specific practice conditions of their group.

Overall performance was better predicted by relative $H$ angle than by form ratio. This might be related to the following (cf. Galanis et al., 1998). Relative $H$ angle is defined using the horizon and a point on the aircraft, both of which are easily detectable. Relative $H$ angle is therefore detectable even from long distances to the runway. In contrast, changes that occur in the form ratio of the runway are easier to detect from shorter distances, for which the optical size of the runway is large, than for longer distances, for which the optical size of the runway is small.6

General Discussion

The present study concerns variability of practice and landing. Experiment 1 compared two practice conditions. Participants in the variable group practiced with trials in which variability was applied to three factors (runway width, texture density, and eye height in the cockpit). Participants in the constant group practiced without such variability. The improvement in performance in the acquisition phase was similar for both groups. The level of performance was also similar in a retention test. However, in a transfer test, which was performed with novel values on the three factors, the variable group performed better than the constant group.

We propose that variability of practice effects are related to the education of attention, which proceeds more quickly if initially used variables are less useful in practice (Fajen & Devaney, 2006; Jacobs et al., 2001). It is reasonable to believe that participants in Experiment 1 initially relied to some extent on relative $H$ angle and on form ratio (Galanis et al., 1998; Mertens, 1981; Mertens & Lewis, 1982). The usefulness of these variables was reduced in the variable practice because of the variability in runway width and eye height. This may have led participants to change in variable use and to come to rely on the more useful variables. Among the more useful variables is the absolute $H$ angle, which is not affected by the type of variability that was applied.

Experiment 2 also compared two practice conditions. In the fixed cockpit condition, the eye position in the cockpit was held constant and variability was applied to texture density and runway width. In the fixed runway condition, the runway width was held constant and texture density and eye height changed from trial to trial. Transfer tests were conducted with fixed cockpit and fixed

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Table 2

<table>
<thead>
<tr>
<th>Participant</th>
<th>Best fitting $w$ Value</th>
<th>Fit (m)</th>
<th>Relative $H$ angle Value (°)</th>
<th>Fit (m)</th>
<th>Form ratio Value</th>
<th>Fit (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed cockpit group</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.91</td>
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<td>8.54</td>
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<tr>
<td>2</td>
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<td>5.15</td>
<td>6.41</td>
<td>1.84</td>
<td>16.02</td>
</tr>
<tr>
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<td>5.06</td>
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<td>1.88</td>
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<tr>
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<td>13.95</td>
</tr>
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<td>14.65</td>
</tr>
<tr>
<td>Fixed runway group</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.80</td>
<td>9.99</td>
<td>5.54</td>
<td>10.21</td>
<td>1.72</td>
<td>15.30</td>
</tr>
<tr>
<td>7</td>
<td>0.87</td>
<td>8.75</td>
<td>5.41</td>
<td>8.96</td>
<td>1.67</td>
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</tr>
<tr>
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<tr>
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<tr>
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<td>1.73</td>
<td>14.60</td>
</tr>
</tbody>
</table>

Note. Fit = Averaged absolute deviations between predicted and observed approach trajectories.

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6 Consistent with this observation, Galanis et al. (1998) proposed a model according to which pilots predominantly use $H$-angle relations at long distances from the runway and gradually change to the use of the form-ratio relations during the approach. Note that such changes in variable use during the approach are inconsistent with the present version of our quantitative model. Our model assumes that an individual uses a single (compound) variable throughout the two transfer phases, and the model aims to identify the best-predicting variable. This is in line with the direct-perception approach (Michaels & Carello, 1981), which assumes that a single higher-order variable is used in a broad range of circumstances.
runway conditions. The fixed cockpit group maintained a high level of performance in the fixed-cockpit transfer test but not in the fixed-runway transfer test. The opposite pattern of results was observed for the fixed runway group. During practice, participants gradually shifted toward the informational variables that were useful under the specific practice conditions of their group. Hence, these results further support our interpretation of variability of practice effects in terms of the education of attention. In the following we relate our findings to the specificity of practice hypothesis and compare our interpretation of variability of practice effects to other interpretations.

The Specificity of Practice Hypothesis

The acquisition of perceptual-motor skills depends on the conditions under which skills are practiced (Proteau, Marteniuk, Girouard, & Dugas, 1987; Proteau, Marteniuk, & Lévesque, 1992). This phenomenon is often referred to as the specificity of practice hypothesis (Proteau, 1992; Tremblay & Proteau, 1998). Pioneering research concerning specificity of practice has been performed with manual aiming tasks. Participants in the study reported by Proteau et al. (1987), for example, practiced an aiming task in a full vision condition (hand and target were both visible) or in a restricted vision condition (only the target was visible). Participants performed a retention test with restricted vision after the acquisition phase. The full vision group outperformed the restricted vision group. This result is representative for the body of work concerning specificity of practice.

In our Experiment 2, participants performed better in the transfer test with the specific experimental conditions that they encountered in the acquisition phase than in the other transfer test. This result is consistent with the specificity of practice hypothesis and can hence be interpreted as support for that hypothesis. Our explanation is also similar to the explanation proposed by Proteau and colleagues. Proteau and colleagues argue that learning is specific to the conditions under which skills are acquired because learners come to use sensory information that is available to them during the acquisition phase (e.g., Proteau et al., 1992). Withdrawing or adding relevant sources of information in a retention test after the acquisition phase therefore has a detrimental effect on performance.

There are, however, substantial differences between our study and the ones by Proteau and colleagues. First, the experimental manipulations differ. The manipulations of Proteau and colleagues typically include switching the lights in the experimental room on or off, with the result that information about the moving limb is either available or not available. Our manipulations affect the usefulness of the informational variables, not their availability. For example, in our practice conditions the relative angle is always available, and participants can always fly so as to keep this variable constant. The crux of our manipulations is that in some conditions the use of this variable leads to more stable and satisfactory performance than in other conditions.

![Figure 7](image1.png)

**Figure 7.** Left: Gaussian distributions that indicate the best-fitting $w$ values in the combined transfer tests for both experimental groups of Experiment 2. Right: Percentage of white-white-red-red feedback predicted by the use of the $w$ values on the horizontal axis.

![Figure 8](image2.png)

**Figure 8.** Frequency of requests during the acquisition phase for participants in the fixed cockpit group (P1 to P5) and fixed runway group (P6 to P10) of Experiment 2.
A second and related difference is that our analyses provide a more detailed description of the available informational variables, of the usefulness of these variables, and of how participants change in variable use. This more precise description also allows more precise predictions. Consider two practice conditions in which the same informational variable, or locus in the information space, is the most useful variable, but in which the steepness of the usefulness function of the variables differs. Both our interpretation and the specificity of practice hypothesis predict that learners who practice under such conditions converge toward the use of the most useful variable. A more precise description of the usefulness function, however, leads to the additional prediction that the steeper the usefulness function, the faster the learning. Empirical results consistent with this prediction have been reported in Experiment 2 of Jacobs, Silva, and Calvo (2009). We next consider other explanations of variability of practice effects.

**Variability of Practice and Schema Theory**

The classical explanation for variability of practice effects is the one of Schmidt’s (1975) schema theory. According to schema theory, learning consists of updating ones knowledge about the relation between parameters of a GMP and movement outcomes. In Schmidt’s view, variable practice provides the learner with a more useful sample of parameter-set/movement-outcome pairs than constant practice. Schmidt’s theory is typically applied to actions with short durations, such as reproducing ones signature. Landing an aircraft is an action with a much longer duration. In addition, the outcome of the action of landing is not determined by the control executed by the pilot, but by his or her control in interaction with changing circumstances. Schmidt’s (1975) schema theory therefore does not provide a satisfactory explanation for the results of the present experiments.

**Noise and Local Minima**

Perceptual-motor learning can often be portrayed as a continuous movement through a space. In dynamical systems theory it is common to claim that the movement through the space optimizes a certain performance-related quantity, referred to as potential function (Strogatz, 1994). Such processes can be illustrated with the analogy of a particle sliding down the slope of the potential function (see Figure 9). This type of learning can be trapped in local minima. A certain level of variability, then, often equated with noise, can be beneficial because noisy systems are less easily trapped in local minima. For example, a sufficient amount of random movement allows the particle in Figure 9 to escape from the local minimum (left well) and proceed to the global minimum (right well). In the context of variability of practice effects this explanation is often used metaphorically, without precise definitions of the spaces, of the potential functions, and of the local minima in the potential functions.

An example of an explanation in terms of noise and local minima can be found in Schöllhorn et al. (2009), who argued that:

In the case of a local minimum (corresponding to a depression in the landscape) any small change of behavior will actually lead to a degraded performance score and therefore requires some external or internal perturbation (noise). This perturbation is often provided by the coach so as to escape from this false minimum and progress toward the ultimate performance goal at the global minimum of the landscape (pp. 322–323).

Applied to our results, one could argue that the higher noise level in the variable practice allowed participants to avoid being trapped in local minima, in contrast to the lower noise level in the constant practice.

The dynamical systems explanation in terms of noise and local minima is more similar to our explanation than Schmidt’s (1975) cognitivist one. Even so, important differences exist. One of these differences is the following. The dynamical systems explanation assumes that local minima exist with variable practice conditions as well as with constant practice conditions. With variability, or noise, the potential function is assumed to be the same, but the system is able to escape from the minima. In contrast, in our interpretation practice conditions determine the shape of the potential function or, stated slightly differently, the shape of the usefulness function (cf. Schöllhorn et al., 2006). In the constant practice of Experiment 1, for example, all considered informational variables are equally useful. In representations that use a continuous space this means that the usefulness function is flat. With variability, some variables become less useful (relative angle, form ratio) while others maintain their specificity with approach angle (absolute angle). This means that the usefulness function has a nonzero gradient, or nonzero steepness. Another example of how practice conditions determine the shape of a usefulness function is given in the right panel of Figure 7.

**Potential-Based and Direct Learning**

The question that forms the thread of this study is: Why does more variability lead to quicker learning? We started with the hypothesis that more variability leads to quicker learning because it leads to a lower usefulness of the initially used variables during practice, which has been shown to lead to a quicker change in variable use. We later unpacked this hypothesis as follows: More variability leads to a lower usefulness of the initially used variables, which implies a steeper usefulness curve, or a steeper potential function, and hence implies a quicker change in variable use. Let us mention that this latter hypothesis can be further elaborated. To do so we consider two ways in which learners might move through information spaces.
A first type of theory, referred to as potential-based learning, holds that learners are able to detect the value of a potential function at nearby points in the space, use these values to estimate the direction of the steepest decrease of the potential function, and subsequently move in the direction of the steepest decrease (e.g., Jacobs, Ibáñez-Gijón, Díaz, & Traviño, 2011). This means that the potential function has a causal role in the learning process. In such a learning process, learners infer a direction of movement in the information space from detected quantities that are sampled at multiple points in the space and that by themselves do not specify such a direction. As indicated earlier in this manuscript, we believe our results are consistent with a potential-based learning theory.

The results are also consistent with the related direct learning approach (Jacobs & Michaels, 2007; Michaels, Arzamarski, Isenhower, & Jacobs, 2008). Learning is direct if learners directly detect a quantity that specifies a direction and speed of movement in the information space. Such a quantity is referred to as information for learning (e.g., Jacobs et al., 2009). Rather than inferring the direction of steepest decrease of a potential function from detected values of the potential function, sampled at multiple points in the space, learners are claimed to be sensitive to a higher-order quantity that specifies such a direction. This approach holds that more learning occurs if and only if the exploited information for learning specifies more learning. To explain the beneficial effect of variability of practice this approach must therefore claim that the information for learning specifies more learning if one performs an action under variable conditions than if one performs the action under constant conditions.

Using these concepts we obtain a slightly modified version of our hypothesis: More variability leads to a lower usefulness of the initially used variables, which is expected to go together with information for learning that specifies more movement in the information space, and hence implies a quicker change in variable use. The direct learning view, however, is more difficult to illustrate than the potential-based view, at least as long as one does not have a clear intuition about what the information for learning for a particular task is. In addition, our intuition is that direct theories might provide better explanations for learning than potential-based theories for tasks that have shaped biological systems during long evolutionary processes, but one might wonder whether landing aircraft is such a task. A more detailed consideration of potential-based and direct processes can be found in Jacobs et al. (2011).

Conclusions and Implications

To summarize, our results reveal that variability of practice is beneficial for the learning of the final approach phase. We propose an explanation for these results that is different from the explanation based on Schmidt’s schema theory and from explanations based on noise and local minima. We believe that variability of practice effects are related to the education of attention. The education of attention is hypothesized to proceed faster with variable conditions in part because the usefulness of initially used informational variables is reduced in such conditions.

On a practical level the results of the present study have important implications for the design of flight training programs. In many current training programs low levels of practice variability are used because of the fact that it is considered desirable for the flight simulation to always maintain a high level of similarity with real flight conditions (Gibb, Gray, & Scharff, 2010). For example, varying the eye height of the pilot or removing/adding ground texture during training would be seen as unnatural manipulations. However, the present results indicate that these are exactly the types of manipulations that are needed to result in optimal pilot training.

References


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