

Analysis of a Perceptual Skill

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Four experiments were conducted with a trajectory-intersection (video game) task to identify the information-processing mechanisms responsible for performance differences associated with initial ability and practice. We concluded that proficiency differences associated with initial ability are largely attributable to differences in the revision of processing operations and, to a lesser extent, to differences in the effectiveness of some component operations. Practice-related proficiency differences were less associated with component revision differences, and there was no evidence that the performance improvement caused by practice was accompanied by an increase in the effectiveness of individual components.

The purpose of the present study is to examine the nature of skill on a relatively simple perceptual task. Both the performance of elementary component operations and the pattern of component execution are examined in subjects differing in level of performance in their first encounter with the task, and in comparisons before and after practice on the task, to determine whether the same processing characteristics are associated with each type of performance proficiency.

Experimental Task and Process Model

A fairly novel experimental task—judging the temporal intersection of two trajectories—served as the activity in which skill differences were examined. A target moved along a left-to-right trajectory at a variable speed and angle, and the subject was to control the initiation time of the vertical trajectory of a projectile with the goal of making the projectile and target trajectories intersect in space at the same point in time. This task is somewhat similar to an automobile driver attempting to judge the gap (target) between cars that is sufficient to allow one to merge into the flow of traffic. It also resembles the activity of judging the future position of a ball (target) in order to catch, kick, or deflect it, and the activity of leading a moving target in attempting to shoot it. Because of the

mode of presentation (i.e., on a video screen), the current task is probably most similar to certain video arcade games, and indeed this resemblance was maximized with sound effects and an exotic task name ("Photon Phantasy") to capitalize on the interests of college students in such amusements.

The first step in the current investigation consisted of the development of an initial model of how the trajectory-intersection task is performed in order to provide a basis for deriving hypotheses about the factors contributing to superior performance. Several other studies have used a similar task (e.g., Gerhard, 1959; Gottsdanker & Edwards, 1957; Runeson, 1975), but the major finding, that performance was better with increased time to observe the trajectories, was not very helpful in characterizing the specific processes involved in the task. The current model, generated from intuitive speculations, is expressed in the flow chart of Figure 1.¹

The initial component in the model involves determining the position of an imaginary line extending above the launching apparatus where the target is vulnerable for intersection (the *vertical vulnerability area*; VVA). The second component consists of estimating the time that the target will arrive in the VVA above the launching apparatus

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¹ The components in this diagram, as with most such abstract organizational charts, refer to functionally, but not necessarily physically, distinct processes, and the sequential arrangement portrayed suggests a typical, but not necessarily the only, sequence of components.

Model of Processes in Trajectory Intersection Task

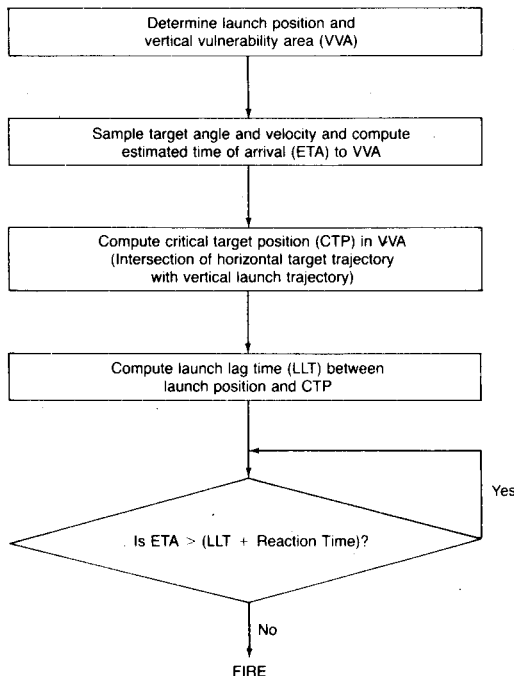


Figure 1. Initial model of the major components involved in the task of initiating a vertical trajectory to intercept a target moving in a horizontal trajectory.

(the *estimated time of arrival*; ETA). We assumed that both the velocity or speed and the angle or direction of the target are used to make these ETAs because both variables contribute to the actual time. Next, on the basis of information about the initial position and angle of the trajectory, the subject is postulated to determine the location in the VVA at which the target will intersect the launch trajectory (the *critical target position*; CTP). Another component involves estimating the time required by the launched projectile to traverse the distance from the launching position to the CTP (the *launch lag time*; LLT).

The final component in the model is a decision phase in which the subject evaluates whether the ETA of the target is equal to the sum of the LLT and one's own reaction time to push the fire button. If the two times match, the subject presses the button, and if the arrival time exceeds the sum of the LLT and reaction time, the subject waits. Two

strategies are possible if the subject reaches the decision stage with ETA less than the sum of the LLT and reaction time: The subject could simply withhold the response, or the fire button could be pressed in what is recognized as a probably futile effort.

Although we do not claim that this model accurately and completely describes how subjects actually perform the trajectory-intersection task, it does have heuristic value in suggesting several possibilities for the nature of skill differences in this task. For example, because the accuracy of the final decision is dependent on the accuracy of each of the prior components, skilled individuals might perform better than unskilled ones simply because they are more effective or efficient in the performance of one or more of the components. This hypothesis is explored in Experiments 1, 3, and 4 by assessing discrimination accuracy of vertical trajectories (Component A), left-to-right trajectories (Component C), ETAs (Component B), and LLTs (Component D).

Another possible reason for proficiency differences is that individuals of differing skill levels might use alternative sequences of components. As an example, although the flow chart of Figure 1 indicates that subjects merely wait (i.e., cycle back only to the decision component), if the arrival time is greater than the sum of LLT and reaction time, it is conceivable that some subjects use this additional time to revise their initial trajectory and time estimates by cycling back to earlier components in the sequence. This hypothesis is explored by examining task performance (hit percentage) as a function of the time the target path was displayed prior to the launch location. If subjects do not revise their initial estimates, the function relating hit percentage to path observation time should be relatively flat because the time beyond that needed for the initial estimate is merely spent waiting. On the other hand, if subjects do revise their estimates by cycling back to earlier components, the accuracy of their estimates is likely to improve with more opportunities for revision. This would result in hit percentage increasing as a function of path observation time.

An interesting question, therefore, is whether the performance difference across

individuals of varying levels of overall proficiency is evident in the rate of gain (slope) or the initial level (x-axis intercept) of the function relating hit percentage to path observation time. A slope difference, with only skilled subjects increasing in accuracy with greater path observation time, would implicate a different pattern of processing components between skilled and less skilled subjects. An intercept difference, however, would suggest that the skill variations are not simply attributable to different amounts of estimate revisions, and consequently, other mechanisms would have to be postulated to account for the performance differences between skilled and unskilled individuals.

Categories of Skill

Although skill broadly refers to proficiency on a specific activity, at least three conceptually distinct categories of skill can be identified (cf. Noble, 1978). The first is practice-mediated skill or expertise in which the skill comparisons are between the same (or comparable) individuals before and after varying amounts of experience performing the activity. However, even at the same level of experience there are often large individual differences in task proficiency and thus another category of skill can be established based on the level of initial ability. Here the skill comparisons are between those individuals performing near the top of the population distribution and those individuals performing near the bottom of the population distribution after comparable amounts of experience on the task. A third manner in which different skill levels might be distinguished is with respect to demographic characteristics. Certain segments of the population (e.g., very young children or older adults) might be known to be deficient to other population groups (e.g., young adults) in a variety of perceptual, cognitive, and motor abilities suspected to be relevant to performance on the task of interest, and thus one might also expect task-proficiency differences to be related to these demographic characteristics.

The examination of several different categories of individual differences allows a comparison of the information-processing mechanisms associated with each type of

skill. Just as it may be unlikely that a given category of skill can be explained by a single information-processing mechanism, so also might it be unreasonable to expect that all skill categories could be explained by the same combination of mechanisms.

Two of the three skill categories described here were investigated in the following manner: Experiments 1, 2, and 3 contrasted individuals in the upper and lower quartiles of the tested population; and Experiment 4 investigated the effects of fairly extensive practice in a sample of young adults. An additional experiment, which was conducted to examine the performance of young and old adults at moderate levels of experience, is also briefly discussed. Experiments 1, 2, and 3 are described together because they were formally similar and differed only in the specific analytical tests administered after the standard trajectory-intersection task. The tests were designed either to assess the effectiveness of component operation or to explore the between-task generality of the observed skill differences. The various tests were designed to be as similar as possible to the standard trajectory-intersection task with the minimum number of modifications necessary for carrying out the relevant manipulation.

Experiments 1, 2, and 3

Method

Subjects

A total of 96 college undergraduates between the ages of 17 and 30 (32 in each experiment) participated in a single 45-min. session.

Apparatus

Stimuli were displayed on a Hewlett-Packard Model 1311A Display Monitor controlled by a PDP 11/03 laboratory computer. Two 10-key telephone keyboards were also connected to the computer to register responses.

Procedure

The standard trajectory-intersection task involved the target (a $1.0^\circ \times 2.0^\circ$ rhombus) moving in a linear path from left to right across the screen. On different trials, the initial position of the target varied from bottom to top along the left vertical axis of the screen, the trajectory angle varied from -13.0° to 34.0° relative to horizontal, and the trajectory speed varied from 22.5° to 45.0° per

sec. The position of the launching apparatus along the bottom horizontal axis of the screen also varied from trial to trial, but the speed of the projectile remained constant at 60° per sec. Across trials, the time from the initiation of the left-to-right trajectory to the VVA ranged from 220 to 1,090 msec, and the LLT to reach the critical target position ranged from 0 to 420 msec.² Different sound effects were associated with the target motion, the projectile motion, and the explosion created by the simultaneous intersection of target and projectile.

Five blocks of the trajectory-intersection task, each consisting of 50 trials, were administered as the first task to subjects in Experiments 1, 2, and 3. Subsequent tasks differed across the three experiments, but were presented in the same counterbalanced order for all subjects. In Experiment 1, yes/no tests of vertical trajectory, left-to-right trajectory, and LLT were administered along with a modified (blanked trajectory) trajectory-intersection task. Subjects in Experiment 2 received a choice reaction time task and three modified trajectory-intersection tasks (constant target, moving launch, and detonation). Method-of-adjustment procedures were used in Experiment 3 to assess accuracy of left-to-right and vertical-trajectory alignment, and precision of target- and projectile-time estimation.

Vertical-trajectory discrimination (yes/no procedure). Trials in this task consisted of a display of the launching apparatus and the projectile at various distances above the launch site. On half of the randomly selected trials the projectile was directly above the launch site (i.e., vertically aligned), and on the other half of the trials the projectile was displayed .6° to the left or right of vertical alignment. The subject was instructed to press a key on the right keyboard when the projectile was vertically aligned with the launching apparatus (i.e., "yes") and to press a key on the left keyboard when the projectile and launch apparatus were out of alignment (i.e., "no"). Two trial blocks, each consisting of 50 trials with a range of projectile-launch site distances, were administered.

Left-to-right-trajectory discrimination (yes/no procedure). The display in this task consisted of a 500-msec presentation of the first 20% of the target trajectory, a 500-msec blank period, and finally a 500-msec presentation of a single dot directly above the launching apparatus. On half of the randomly selected trials the dot was an extrapolation of the target trajectory, and on the other half of the trials the dot was displaced 1.2° above or below the true intersection point. The subject was instructed to press a key on the right keyboard when the dot was aligned with the initial trajectory (i.e., "yes"), and to press a key on the left keyboard when the dot and initial trajectory were out of alignment (i.e., "no"). Two trial blocks, each consisting of 50 trials with a range of trajectory-dot distances, were administered.

LLT discrimination (yes/no procedure). In the standard trajectory-intersection task an auditory signal was presented for the entire duration that the projectile was in motion on the display. The present task capitalized on the correlation between sound duration and projectile distance by presenting, for 500 msec, a display of the projectile displaced above the launch site by a randomly varied distance, followed immediately by a sound. On a randomly selected half of the trials, the duration of the sound corresponded to the time it would have taken the projectile to traverse that distance, and on the other half

of the trials the sound duration was approximately 125 msec too long or too short for the distance displayed. The subject was instructed to press a key on the right keyboard when the sound duration and projectile distance matched, and to press a key on the left keyboard when they did not match. Two trial blocks, each consisting of 50 trials with a range of launch-projectile distances, were administered.

Method-of-adjustment tasks. All four of the tasks using the method of adjustment followed the same general procedure. First, the stimulus configuration was displayed and the subject could either increase or decrease the value of the relevant parameter. The stimulus could then be displayed and the prior steps repeated as frequently as desired, and finally a decision was registered. The "7" and "9" keys on the right keyboard decreased and increased the parameter value, respectively, and the "8" key caused the altered stimulus configuration to be displayed. Any key on the left keyboard resulted in the registration of that parameter setting and initiated the subsequent trial. Each task involved 30 trials with a range of (where relevant) heights, angles, and speeds of the target, and horizontal positions of the launch apparatus.

Because the four tasks were designed to assess the efficiency of the components proposed in Figure 1, they were termed the VVA, ETA, CTP, and LLT tests. In the VVA test, the stimulus configuration was the launching apparatus and a single dot, which was to be adjusted in the horizontal dimension to be in alignment with the launching apparatus. In the CTP test, the stimulus configuration was 150 msec of the target trajectory and a single dot, which was to be adjusted in the vertical dimension to be in alignment with the initial trajectory.

The ETA and LLT tests involved adjustments of the time delay between two stimulus events. The first stimulus event in the ETA test was the initial 150 msec of the target trajectory, and the second event was a vertical line displaced across trials at various distances to the right of the trajectory. In the LLT test, the first stimulus event was the display of the launching apparatus and the second event was a horizontal line displaced across trials at various distances above the launch site. In both tests the subject adjusted the duration between the offset of the first stimulus event and the onset of the second event to correspond to the time required by the target (ETA test) or the projectile (LLT test) to traverse the indicated distance.

Choice reaction time. A choice reaction time task was administered to determine whether performance on such an elementary task would be correlated with performance on the more complicated trajectory-intersection activity. Either an X or an O was displayed after a fixation stimulus consisting of four dots at the corners of a 1.2° × 1.8° rectangle. Subjects were instructed to press the left key for X and the right key for O. A minimum of 75 trials, the first 25 of which were practice, composed a trial block. The mean reaction time for the last 50 trials with an accuracy of 90% or greater served as the primary dependent variable.

² This combination of times resulted in some trials in which it was physically impossible to achieve a trajectory intersection without pressing the fire button before the appearance of the target.

Blanked trajectory. This task was similar to the standard trajectory-intersection task except that only the first 217 msec (approximately 20%) of the target trajectory was displayed. The target continued on its original path and the subject still attempted to launch the projectile to intersect the target, but the judgments had to be based on an extrapolation because only the initial portion of the target trajectory was actually displayed. Two trial blocks of 50 trials each were presented.

Constant target. The constant-target version of the trajectory-intersection task was identical to the standard version except that the speed and angle of the target did not change from trial to trial. The height of the target and the horizontal position of the launching apparatus varied randomly across trials, but the target speed and angle remained constant at intermediate values (i.e., 33.8° per sec, and 0°, respectively).³ Two trial blocks of 50 trials each were presented.

Moving launch. The distinguishing feature of this task was that the launching apparatus moved from right to left across the screen, at 15° per sec, while the target was moving from left to right. Launching occurred at the moment of activation by the key press, and thus the trajectory was vertical from the position of the launching apparatus at the time of the key press. Because the launching apparatus always began at the far right, this task involved longer average path observation times than the standard task, but all other aspects of the task remained unchanged. Two trial blocks of 50 trials each were presented.

Detonation. This task differed from the standard trajectory-intersection task in having a continuous vertical line on the screen instead of a launching apparatus. The line was described as a mine field that was to be detonated at the exact moment the target intersected it. Unlike the standard task, the detonation task contains no LLT because the entire VVA is simultaneously activated with the button press. Two trial blocks of 50 trials each were presented.

Results

The high- and low-ability groups were distinguished on the basis of the average hit percentage for Blocks 2–5 (200 trials) of the standard trajectory-intersection task. (The first block of trials was considered practice and the data were not analyzed.) Subjects in the top quartile of the distribution of scores in each experiment served as the high-ability group, and those in the bottom quartile constituted the low-ability group. The mean hit percentages for the high-ability groups were 33.9% for Experiment 1, 34.9% for Experiment 2, and 37.6% for Experiment 3; means for the low-ability groups were 19.4% for Experiment 1, 19.0% for Experiment 2, and 20.5% for Experiment 3. As expected, the ability differences were highly significant in each experiment: Experiment 1, $t(14) =$

12.39, $p < .001$; Experiment 2, $t(14) = 10.55$, $p < .001$; Experiment 3, $t(14) = 12.82$, $p < .001$.

The high-ability groups were predominantly male (8 out of 8 in Experiments 1 and 3, 6 out of 8 in Experiment 2), whereas the low-ability groups were predominantly female (7 out of 8 in Experiments 1 and 2, 6 out of 8 in Experiment 3). The reported numbers of minutes per week spent playing video games over the last 6 months were 68.1 versus 24.1, $t(14) = 2.66$, $p < .05$, for the high- and low-ability groups in Experiment 1, respectively; 67.8 versus 39.0, $t(14) = 1.19$ (*ns*), for the comparable groups in Experiment 2; and 133.0 versus 6.8, $t(14) = 2.73$, $p < .05$, for the comparable groups in Experiment 3. It is not clear whether the video game experience was a cause, or merely another consequence, of what are termed initial ability differences. For the purposes of this project, however, initial ability can be operationally defined as level of performance on the first encounter with the current experimental task.

Performance on the vertical-trajectory, left-to-right-trajectory, and LLT discrimination tasks was expressed as percentage correct in the yes/no decision. These data were analyzed with 2×3 (Ability \times Task Difficulty) analyses of variance (ANOVAS). The task-difficulty variable was created by dividing a relevant distance dimension into equal thirds. In both the vertical-trajectory discrimination and LLT discrimination tasks the distance was that between the launch site and the projectile position. The distance in the horizontal-trajectory-discrimination task was that between the end of the initial trajectory and the dot whose alignment was to be judged. In all cases, we assumed that the shorter the relevant distance, the easier the task.

The ANOVA on the data from the vertical-trajectory-discrimination task revealed a nonsignificant effect of ability ($F < 1.0$), but a significant difficulty effect, $F(2, 28) = 113.06$, $MS_e = 29.20$, $p < .0001$, and a sig-

³ The target is not stationary in this task, but the speed and direction of target motion remained constant across trials instead of varying from trial to trial as in the standard task.

nificant Ability \times Difficulty interaction, $F(2, 28) = 4.35$, $MS_e = 29.20$, $p < .05$. Bonferroni t tests at each level of difficulty indicated that the high-ability subjects were more accurate than the low-ability subjects only at the easiest difficulty level: At the easy level (84.6% vs. 77.1%), $t(14) = 2.78$, $p < .01$; at the moderate level (67.5% vs. 71.0%), $t(14) = -1.20$ (*ns*); and at the difficult level (52.3% vs. 52.4%), $t(14) = -.05$ (*ns*).

The ANOVA on the left-to-right-trajectory-discrimination data indicated significant effects of ability, $F(1, 14) = 6.95$, $MS_e = 70.21$, $p < .05$; difficulty, $F(2, 28) = 25.02$, $MS_e = 73.45$, $p < .0001$; and Ability \times Difficulty, $F(2, 28) = 3.74$, $MS_e = 73.45$, $p < .05$. Bonferroni t tests at each level of difficulty revealed that ability differences were significant only at the easiest level of difficulty: at the easy level (88.4% vs. 75.3%), $t(14) = 3.06$, $p < .01$; at the moderate level (66.9% vs. 58.0%), $t(14) = 2.07$ (*ns*); and at the difficult level (62.8% vs. 65.6%), $t(14) = -.67$ (*ns*).

No effects were significant in the ANOVA on the data from the LLT discrimination task: ability, $F(1, 14) = 1.48$, $MS_e = 253.23$, $p > .20$; difficulty, $F(2, 28) = 2.91$, $MS_e = 147.86$, $p > .05$; and Ability \times Difficulty, $F(2, 28) = 1.21$, $MS_e = 147.86$, $p > .30$. The overall mean level of performance was 65.1%.

Performance on the method-of-adjustment tasks was expressed in terms of the constant error (mean error of adjustment) and the variable error (standard deviation of the adjustments) for each of three levels of task difficulty (close, middle, or far distances of the relevant parameter).

The ANOVA on the constant error for the ETA task revealed that the high-ability subjects produced significantly longer time intervals, and greater errors, than the low-ability subjects—236 msec vs. 57 msec, $F(1, 14) = 10.84$, $MS_e = 35,438.74$, $p < .01$ —but neither the task difficulty nor Ability \times Difficulty Effects approached significance ($p > .10$). Only the task-difficulty effect was significant ($p < .05$) with the variable error measure (close = 130 msec, middle = 169 msec, far = 180 msec), $F(2, 14) = 6.33$, $MS_e = 1718.72$, $p < .01$.

There was a significant ability difference on the constant error measure for the LLT

task with the high-ability subjects producing longer time intervals, but smaller errors, than the low-ability subjects (−97 msec vs. −293 msec), $F(1, 14) = 11.82$, $MS_e = 38,916.74$, $p < .005$. The task-difficulty effect was also significant (close = −153 msec, middle = −208 msec, far = −223 msec), $F(2, 28) = 5.84$, $MS_e = 3735.97$, $p < .01$, but not the Ability \times Difficulty interaction ($F < 1.0$). No effects were significant in the analysis of variable error (all $ps > .10$).

The analyses of the measures from the CTP task indicated that only the difficulty effect for the constant error measure was significant (close = $.30^\circ$, middle = 0° , far = $-.41^\circ$), $F(2, 28) = 8.66$, $MS_e = 41.00$, $p < .005$. The main effect of ability and the Ability \times Difficulty interaction did not approach significance with either constant or variable error ($ps > .30$), and the difficulty effect with the variable error measure also fell far short of significance ($p > .30$).

The difficulty effect was significant in the VVA task for both constant error (close = $.17^\circ$, middle = $.32^\circ$, far = $.40^\circ$), $F(2, 28) = 31.61$, $MS_e = 1.18$, $p < .0001$, and variable error (close = $.16^\circ$, middle = $.24^\circ$, far = $.28^\circ$), $F(2, 28) = 12.11$, $MS_e = .84$, $p < .0005$. Neither the main effect of ability nor the Ability \times Difficulty interaction was significant for either variable ($ps > .20$).

Although the high-ability group had slightly faster choice reaction time (394 msec at 95% accuracy vs. 427 msec at 94% accuracy), this difference was not statistically significant, $t(14) = 1.26$, $p > .20$.

Performance on each modified trajectory-intersection task was initially assessed with a Group (high-ability vs. low-ability) \times Task (standard vs. modified) ANOVA on overall hit percentage. The task manipulation in this analysis is contaminated with order and practice effects because the standard task was always presented earlier and for more trials than the modified task, but the interaction term indicates whether the ability differences are significantly altered with the modified task. The Group \times Task interaction was significant for the blanked-trajectory, $F(1, 14) = 6.72$, $MS_e = 22.16$, $p < .05$, and detonation, $F(1, 14) = 8.33$, $MS_e = 39.03$, $p < .05$, tasks, but not for the constant-target, $F(1,$

14) = 2.33, $MS_e = 9.05$, $p > .10$, or moving-launch, $F(1, 14) = 1.46$, $MS_e = 20.58$, $p > .20$, tasks.

The constant-target and moving-launch tasks both led to improved performance for high- and low-ability subjects. The mean hit percentages in the constant-target task were 41.4% for the high-ability subjects and 28.8% for the low-ability subjects, $t(14) = 4.65$, $p < .01$. Mean hit percentages in the moving-launch task were 39.6% for the high-ability subjects and 27.6% for the low-ability subjects, $t(14) = 4.06$, $p < .01$.

Performance on the blanked-trajectory and detonation tasks was reduced relative to the standard task, particularly for the high-ability subjects. Hit percentage averaged only 16.1% and 10.3%, respectively, for the high- and low-ability groups with the blanked-trajectory task, $t(14) = 2.16$, $p < .05$. Performance in the detonation task averaged 22.3% for the high-ability subjects and 19.1% for the low-ability subjects, $t(14) = .73$, *ns*.

To summarize the results thus far, it appears that the subjects who perform well on the standard trajectory-intersection task are also somewhat more proficient than poorer performing subjects at making judgments about the alignment of both vertical and left-to-right trajectories, at least when the task difficulty is not too great and a yes/no procedure is used. There is no hint of comparable differences in the accuracy of discriminating the time required for the projectile or target to traverse a specified distance, although high-ability subjects tended to produce longer time intervals than low-ability subjects. There is a trend for high-ability subjects to have faster reaction times than low-ability subjects, but, perhaps because of the small sample size and/or the large variability, this difference failed to reach statistical significance. The ability differences also seem to be rather task specific as two modified versions of the trajectory-intersection task led to much smaller, and in one case, nonsignificant, ability differences.

As noted earlier, trials in the standard trajectory-intersection task varied in the speed of the target trajectory and in the horizontal position of the launching apparatus. For each trial, these values were converted into units

of time (by dividing distance by speed), and hit percentage was then examined as a function of target path observation time. Six groupings of path observation times were formed on the basis of roughly comparable intervals with a minimum of 15 trials in each category. The mean hit percentages for each observation time grouping are displayed in Figure 2.⁴

We conducted 2×6 (Initial Ability \times Time) ANOVAS on the data from each experiment summarized in Figure 2. The same pattern of results emerged with each set of data as all effects were statistically significant: ability, $F(1, 14) > 58.2$, $MS_e < 143.4$, $p < .0001$; time, $F(5, 70) > 17.6$, $MS_e < 130.0$, $p < .0001$; Ability \times Time, $F(5, 70) > 2.7$, $MS_e < 130.0$, $p < .05$.

The patterns portrayed in Figure 2, in conjunction with the significant Ability \times Time interactions, indicate that the high-ability subjects increased their hit percentage with additional path observation time, whereas the low-ability subjects either did not, or did so to a much lower extent. On the basis of the argument presented earlier, this finding can be interpreted as indicating that only the high-ability subjects were revising their judgments by recycling through the component sequence in the time between the initial estimate and the arrival of the target at the launch position. The functions of Figure 2 are remarkable, not only with respect to how clearly this trend is represented but also in the degree to which the three independent experiments yielded very similar results.

Further confirmation of the hypothesis that high-ability subjects differ from low-ability subjects in engaging in more extensive updating of the decision estimates is available from the data of the two modified trajectory-intersection tasks in which ability differences were significantly reduced. First consider the blanked-trajectory task in which the target

⁴ We conducted two additional analyses with (a) path observation times corrected for variations in LLT due to targets at varying heights and (b) average miss distances substituted for hit percentages. The direction of the misses shifted from too late to too early with increased path observation time, but otherwise the results of these analyses were nearly identical to those previously described.

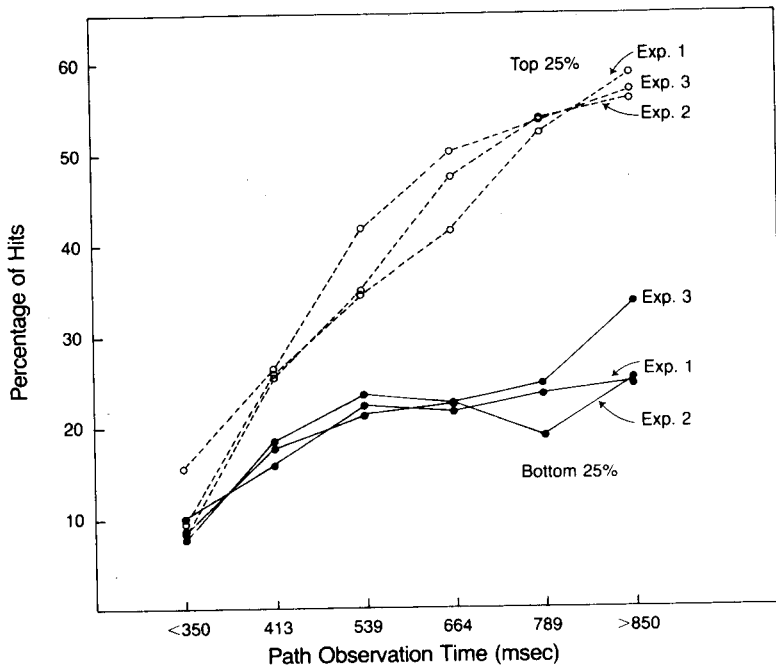


Figure 2. Percentage of hits in the standard trajectory-intersection task as a function of time to observe the target trajectory in Experiments 1, 2, and 3. (The dotted lines are the data from subjects in the top quartiles of the sample, and the solid lines are the data from subjects in the bottom quartiles of the samples.)

path is visible for only the first 217 msec of the total trajectory. Blanking out the subsequent target trajectory should eliminate the opportunity for revisions beyond the initial estimate, and consequently, the performance differences between high- and low-ability groups should be reduced or eliminated if much of the superiority of high-ability subjects is due to their more frequent revision of component estimates. We examined this implication by analyzing the data from the blanked-trajectory task in terms of the six groupings of path observation (continuation) time. Mean hit percentages for the two ability groups are displayed in Figure 3. An ANOVA indicated a small but significant effect of ability, $F(1, 14) = 4.62$, $MS_e = 191.63$, $p < .05$, but nonsignificant effects of time, $F(5, 70) = 2.32$, $MS_e = 78.41$, $p > .05$, and Time \times Ability, $F(5, 70) = 1.26$, $MS_e = 78.41$, $p > .25$.

A comparison of Figures 2 and 3 indicates that not only was the ability difference reduced but the trend for high-ability subjects to improve hit percentage with increased

path continuation time was also completely eliminated. Both of these results are consistent with the interpretation that a major factor responsible for the ability differences in the standard task is the more frequent decision updating among the high-ability subjects.

The detonation version of the trajectory-intersection task provides another opportunity for examining the correspondence between ability differences and the monotonically increasing functions relating hit percentage to path observation time. The relevant data are illustrated in Figure 4. An ANOVA revealed that only the time effect was significant, $F(5, 70) = 5.85$, $MS_e = 143.55$, $p < .001$ (other F s < 1.0). The complex relationship between hit percentage and path observation time is difficult to explain, but it is noteworthy that this version of the trajectory-intersection task resulted in the elimination of both the ability difference and the linear trend between hit percentage and path observation time for high-ability subjects.

Because the constant-target and moving-

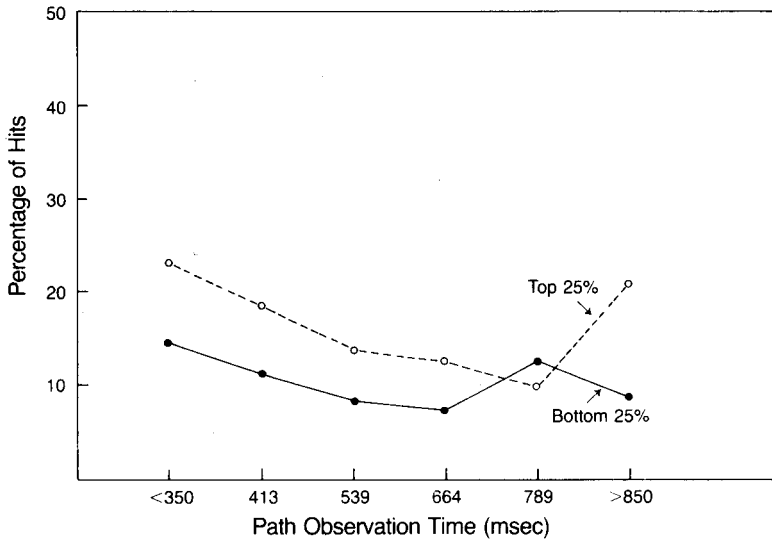


Figure 3. Percentage of hits in the blanked-trajectory task as a function of continuation time of the target trajectory in Experiment 1. (The labels refer to the top and bottom quartiles of the sample of subjects. Note that although the target trajectory was only visible for the first 217 msec, it continued along the same path for the times indicated.)

launch versions of the trajectory-intersection task allow normal updating of target-trajectory information, the interpretation proposed here would lead to the expectation that ability differences would be exhibited in the same manner as observed in the standard

version of the task. As noted earlier, this was indeed the case, and thus the results from these tasks are also consistent with the suggestion that at least part of the ability differences are attributable to more frequent revision of decision estimates.

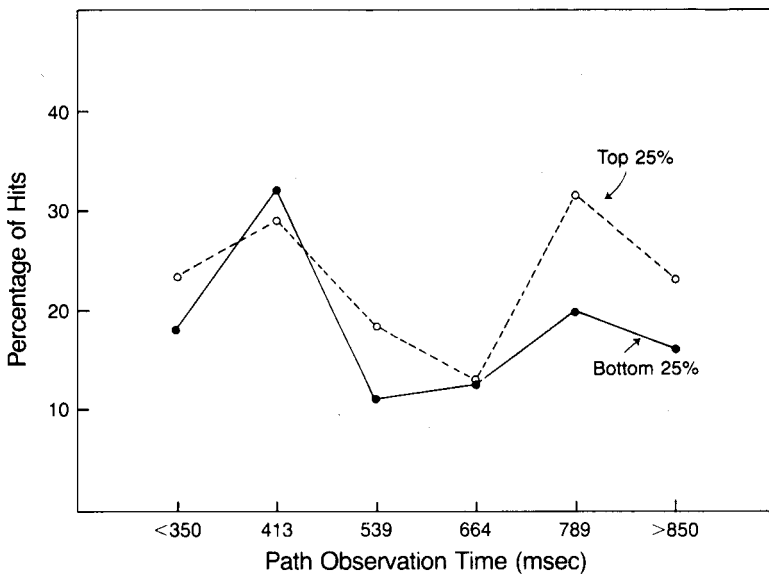


Figure 4. Percentage of hits in the detonation task as a function of time to observe the target trajectory in Experiment 2. (The labels refer to the top and bottom quartiles of the sample of subjects.)

Table 1
Summary of Component-Effectiveness Tests

| Component | Measure | Task difficulty | | Ability |
|-----------|----------------|-----------------|--------|----------------|
| | | Exp. 1 & 3 | Exp. 4 | |
| VVA | Yes/No | X | X | X ^a |
| | Adjustment | | | |
| | Constant error | X | X | |
| | Variable error | X | X | |
| ETA | Adjustment | | | |
| | Constant error | | | X |
| | Variable error | X | X | |
| CTP | Yes/No | X | X | X ^a |
| | Adjustment | | | |
| | Constant error | X | X | |
| | Variable error | | | |
| LLT | Yes/No | | — | |
| | Adjustment | | | |
| | Constant error | X | X | X |
| | Variable error | | X | |

Note. An X indicates that the effect was statistically significant ($p < .05$); a dash indicates that the information was not applicable. VVA = vertical vulnerability area; ETA = estimated time of arrival; CTP = critical target position; LLT = launch lag time.

^a These effects were significant only at the easiest level of difficulty.

Discussion

The main purpose of Experiments 1, 2, and 3 was to identify some of the factors correlated with performance differences observed in a haphazard sample of individuals. As it turned out, the subjects with extreme scores also differed in sex distribution and self-reported experience playing potentially related video games. These results indicate that the three skill categories identified in the introduction are frequently not mutually exclusive because the present experiments attempted to investigate skill as initial ability, but the individuals in the extreme ability groups also differed on experience and demographic (i.e., proportion of males) dimensions. Although these differences make it difficult to determine why the individuals differed in proficiency, the major focus of Experiments 1, 2, and 3 was to identify processing factors responsible for the existing

ability differences, and this goal is not compromised by the characteristics of the samples.

The results of Experiments 1, 2, and 3 present an intriguing, but still incomplete, picture of the nature of skill as initial ability on the trajectory-intersection task. With respect to the model illustrated in Figure 1, there is evidence that the skilled subjects may be more effective than the unskilled subjects at performing some of the component operations. It can be seen in Table 1, which summarizes the major results from the tests of component effectiveness, that an ability effect was obtained in each of the components investigated. Perhaps more remarkable, however, is the small number of significant ability effects relative to the number of significant task-difficulty effects. Seven of the 11 measures were found to be sensitive to the difficulty level of the task, and all of these results were replicated in Experiment 4. Therefore, these seven measures have face validity in that performance was inversely related to task difficulty. However, only three of these yielded significant ability effects, and then only at the easiest difficulty level for the VVA and CTP components.

It is interesting to note that the high-ability subjects produced significantly longer time estimates than low-ability subjects in both the LLT and ETA tests. Unfortunately, without further data one can only speculate as to whether the longer subjective time estimates are a cause, or an effect, of the performance differences with which they are correlated. It is also noteworthy that both high- and low-ability subjects apparently had illusory perceptions of the trajectory velocities as the left-to-right velocity was consistently underestimated (positive constant errors), and the vertical velocity was overestimated (negative constant errors). Runeson (1975) reported a similar misperception of velocity, but we have no satisfactory explanation for this illusion, or the fact that it apparently reverses from vertical to horizontal orientations.

Perhaps the strongest conclusion possible at the present time is that the skilled subjects appear to execute the components in a different manner than the less skilled subjects. This inference is derived from the functions portrayed in Figures 2 and 3, which are con-

sistent with the interpretation that the high-ability subjects cycle through prior components with additional time to observe the target trajectory, whereas the low-ability subjects merely wait. In terms of the model portrayed in Figure 1, the low-ability subjects seem to be accurately characterized by the loop on the decision component, whereas the high-ability subjects are better represented with a loop to earlier components such that the decision estimates become progressively more precise with additional time.

Experiment 4

The purpose of Experiment 4 was to investigate the processes contributing to practice-related skill on the trajectory-intersection task. Some relevant data were available from eight young adults and eight older adults who performed two trajectory-intersection tasks for 50 experimental sessions in the context of a larger project (Salthouse & Somberg, 1982). Unfortunately, because of the time requirements of the other activities in the project, an average of only 12.5 trials per task per session was presented and no tests of component effectiveness were carried out. However, comparisons of performance on the first and last 188 trials (with an average of 288 intervening trials) revealed significant age (i.e., young = 31.2%, old = 18.3%) and practice (i.e., early = 22.9%, late = 26.7%) effects, and a significant Age \times Path Observation Time interaction with young subjects having steeper slopes than old subjects. The Practice \times Path Observation Time interaction was significant for young but not for old subjects, with the direction of the interaction indicating that the slope of the function relating hit percentage of path observation time was steeper with increased practice.

Although the age and practice differences were interesting, the absence of tests of component effectiveness and the rather small effect of practice (i.e., 3.8%) weakened the informativeness of the results. The current experiment attempted to produce greater effects of practice by providing many more practice trials (i.e., 1,800 vs. 288). In addition, tests of component effectiveness were administered after practice to determine whether some of the expected performance improve-

ment was attributable to more accurate spatial and temporal discriminations. A modified matched-groups design was used to capitalize on the availability of data from the pool of subjects in Experiments 1 and 3. A majority of females were used as subjects to minimize the amount of preexperimental practice with related tasks.

Method

Subjects

Eight young adults with a mean age of 22.6 years (seven females and one male) participated in five 1-hour sessions over a period of 2 weeks. Each received \$20 for participating.

Apparatus

The apparatus was identical to that of the preceding experiments.

Procedure

Ten 50-trial blocks of the standard trajectory-intersection task were administered on Sessions 1 through 4. The first and last five trial blocks in the experiment were identical, but the remaining 35 trial blocks (i.e., 5 on Session 1 and 10 each on Sessions 2, 3, and 4) had randomly selected values of target speed, target angle, target height, and launch location. On Session 5, the subjects received five trajectory-intersection trial blocks followed by method-of-adjustment tests of horizontal (CTP) and vertical (VVA) trajectory alignment, horizontal (ETA) and vertical (LLT) trajectory timing, and forced-choice tests of horizontal and vertical trajectory alignment.

The instructions encouraged subjects to attempt to improve their performance as much as possible during the practice periods. As an additional incentive, the individual exhibiting the greatest improvement from the first to the fifth session received a \$20 bonus.

Results

The mean percentage of hits in the trajectory-intersection task increased from 26.1% in Blocks 2-5 of Session 1 to 36.6% in Blocks 2-5 of Session 5, $t(7) = 3.38$, $p < .05$. The significant effect of practice indicates that the provision of 1,800 trials between the first and second testing sessions did indeed lead to substantial performance improvements.

Figure 5 illustrates hit percentage as a function of path observation time for early (Session 1) and late (Session 5) phases of practice. An ANOVA indicated that the practice, $F(1, 7) = 38.01$, $MS_e = 84.43$, $p < .0005$, and time $F(5, 35) = 53.76$, $MS_e = 99.99$,

$p < .0001$, effects were significant, but the Practice \times Time interaction was not, $F(5, 35) = 2.16$, $MS_e = 84.43$, $p > .05$. These statistical trends, in conjunction with the pattern portrayed in Figure 5, indicate that the linear relationship between path observation time and hit percentage was evident at both stages of practice, and that the additional experience led to an increase in hit percentage but with only a slight (nonsignificant) steepening of the path observation time/hit percentage function.

To make comparisons of the effects of practice on component effectiveness, the current subjects were contrasted with subjects from Experiment 1 and Experiment 3 and matched on the basis of overall hit percentage for Blocks 2–5 of Session 1. This allowed a direct examination of the effects of practice on component effectiveness because the subjects from the earlier experiments received the component tests immediately after Blocks 2–5 of Session 1, whereas the subjects from the current experiment received 40 additional blocks (2,000 trials) before the component tests. The matching was quite close because only 8 subjects had to be matched

and both Experiments 1 and 3 contained pools of 32 subjects. The mean hit percentages of the 8 control subjects from the two previous experiments were both 26.1%, exactly the same as the mean of the present experimental subjects on Session 1.

The results of the ANOVAS conducted on the measures of component effectiveness can be easily summarized. There were no significant practice ($p > .09$) or Practice \times Task-Difficulty ($p > .14$) effects. There is absolutely no evidence that the subjects with additional practice and substantially higher final performance were any more accurate at making relevant discriminations than subjects of comparable initial performance but without the same amount of practice. Task-difficulty effects were significant ($p < .01$) for all but the CTP variable error ($p > .16$) and ETA constant error ($p > .87$) measures.

Discussion

The two major findings of this experiment are that practice-related skill develops without concomitant increases in the effectiveness of spatial and temporal components, or

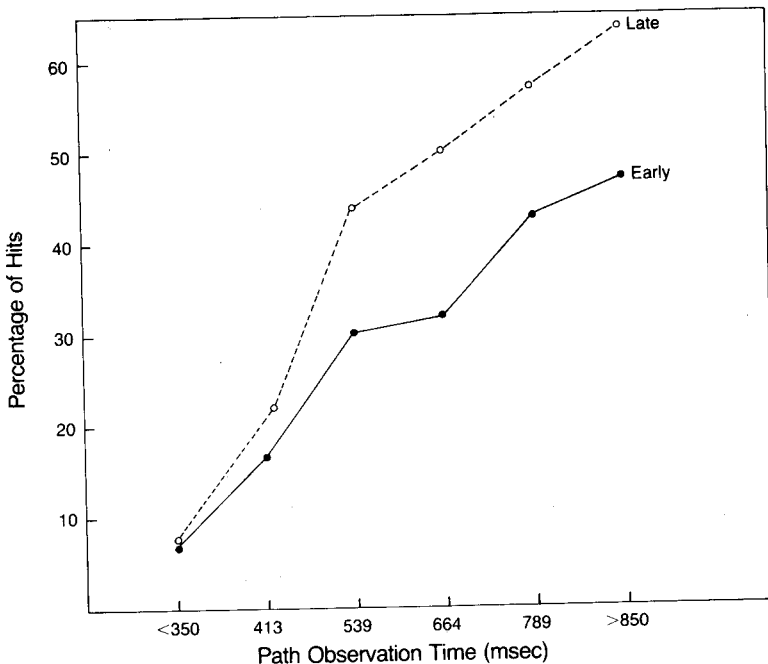


Figure 5. Percentage of hits in the standard trajectory-intersection task as a function of time to observe the target trajectory in Experiment 4. (Early and late refer to the phase of practice.)

dramatic changes in the cycling of component operations. The first result is apparent in the finding that none of the measures of component effectiveness exhibited significant practice effects, despite sizeable differences in overall level of performance (i.e., 26.1% vs. 36.6%). The second result is an inference based on the similar slopes of the functions relating hit percentage to path observation time in Figure 5, and the absence of a significant Practice \times Time interaction.

General Discussion

An intriguing speculation suggested from the results of this study is that different information-processing mechanisms may be contributing to variations in proficiency associated with alternative conceptualizations of skill. For example, the pattern of differences found to account for performance variations associated with practice do not appear to be the same as those accounting for initial ability or age-related performance variations.

One example of this configurational difference is evident in the analysis of the potential differences in the individual components responsible for carrying out specific processing operations. Both forced-choice and method-of-adjustment tests were used to assess the accuracy of the temporal and spatial discriminations postulated to be basic components in the trajectory-intersection task. Some rather slight accuracy differences were found to be associated with initial ability level, but the same tests failed to indicate any differences as a function of practice.

The present tests were designed only to provide information about the effectiveness and not the efficiency of individual components, and therefore it is possible that tests of the time, rather than the accuracy, of the component decisions would have yielded larger and more consistent skill differences. If the limitation were primarily temporal, however, one might have expected the performance differences in the trajectory-intersection task to be reduced with additional time to observe the trajectory and complete the component operations. In fact, the data of Figures 2 and 5 indicate a trend of divergence rather than convergence with increased path observation time, and thus this inter-

pretation has no support at the present time. It also proved impossible to devise a test to assess the effectiveness or efficiency of the decision component in the model of Figure 1, and this component is arguably the most important in the sequence. Despite these limitations, it is still surprising that component effectiveness contributes little to the skill variations, particularly those that are practice-mediated. Salthouse and Somberg (1982) have summarized the results of many studies, and added further results of their own, documenting the effects of practice on elementary aspects of skill, and yet the experience-based improvement in performance on the trajectory-intersection task did not seem to be accompanied by increased accuracy in the relevant components.

One possible reason for the lack of differences in component effectiveness is that individuals at different skill levels used different components to perform the task. This suggestion cannot be definitely ruled out; however, it is difficult to imagine how the task could be performed without components of the type outlined in Figure 1. To estimate the intersection point of two trajectories, both the spatial and temporal aspects of each trajectory must be determined and the information from the two trajectories must be integrated in some manner. The components in Figure 1 therefore appear to provide a necessary and sufficient set to perform the trajectory-intersection task, although alternative levels of specification or detail might be more appropriate for some purposes. For example, it could be argued that velocity and distance are estimated instead of time in the trajectory estimates (e.g., Lappin, Bell, Harm & Kottas, 1975; Rosenbaum, 1975), in which case different sets of component tests might be more appropriate than those that were used. It is clearly necessary to obtain considerably more evidence on a variety of suspected components before dismissing the contribution of improved component efficiency to overall task proficiency, and the present results, although reasonably clear, can only be considered suggestive at the present time.

A difference in the order of the components within the processing sequence does appear to contribute to the skill variations associated with initial ability level and, to a

lesser extent, with practice and adult age. The skilled subjects exhibited a steeper function relating hit percentage to path observation time, and this was interpreted as an indication of more frequent revisions of the component estimates with additional viewing time. The less skilled subjects, particularly those defined in terms of initial ability, had much flatter hit-percentage/path-observation-time functions, suggesting little or no revision of the component estimates with increased time to observe the target path. These differences can be interpreted as evidence that the skilled subjects executed the components repetitively (e.g., ABCDE-ABCDE-ABCDE . . .), whereas the unskilled subjects completed the entire sequence only once (e.g., ABCDE-E-E-E . . .).

It would obviously be desirable to obtain more direct evidence for the hypothesis that skill differences are related to the manner of component execution, but all procedures that were considered had severe limitations. For example, it might seem that eye-movement analyses would prove relevant to this issue, but it is difficult to predict which type of scan pattern would be associated with a given component sequence because much of the information processing could be carried out in the absence of overt eye movements.

A closer examination of Figures 2 and 5 reveals that there are actually two distinct segments of the function relating hit percentage to path observation time, and that the interpretation previously proposed applies best to the segment from 539 to over 850 msec. The first segment, from under 350 to 539 msec, appears to increase for subjects at all skill levels and may be determined more by factors such as speed of component or sequence completion. The data of Figure 5 also suggest that the two segments are differentially affected by practice as only the segment from 539 to over 850 msec appears to exhibit substantial changes with additional experience.

Another result of theoretical significance in the current experiments is the demonstration that the sequence with which elementary components are executed (i.e., ABCDE-ABCDE . . . vs. ABCDE-E . . .) may be a more important determinant of overall skill than the

level of performance on each separate component. Fleishman (1966) and his colleagues have demonstrated that the particular abilities contributing to performance change across stages of practice and the current results are clearly consistent with the suggestion that skill variations are due in part to the reliance on different mechanisms. It has also been argued by many theorists that overall performance may be more dependent on strategies (i.e., sequences of component operation) than on basic abilities or component proficiency (e.g., Allport, 1980; Bartlett, 1972; Edwards, 1979; Glaser, 1980; Lansman, 1981; Pellegrino & Glaser, 1979; Sternberg, 1978; Welford, 1958, 1976). In providing evidence that certain skill variations may be associated with differences in the sequence of component execution, the present study adds substance to the argument that at least some perceptual skill differences are qualitative rather than merely quantitative.

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