

Modularity and hierarchical organization of action programs in human acquisition of graphic skills

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Abstract

If motor or action programs become modules with practice their defining features (e.g. relative timing) should remain relatively invariant in new tasks. To test this hypothesis 24 adults practiced a graphic skill over 100 trials and were transferred to a more complex task enclosing the practiced figure. The data acquired by a digital tablet resulted in total movement and total pause times to draw the figure indicating skill acquisition and variability measures of relative timing and pause time and sequencing referring to features that identify a module. Being transferred to a more complex task did not lead to significant increases in the time to perform the criterion figure embedded in the new pattern. Modularity was evidenced by the stability of relative timing and sequencing shown in the performance of the criterion figure. Hence, it might be that action programs become modules that are then hierarchically organized to form more complex skills.

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Preparing the action prior to execution is essential for skilled behaviour [13] which makes the investigation of motor programs a subject of great interest. Neural substrates of motor programs are being unravelled in a number of studies [6] though their representational structure is a matter of debate. A motor program can be seen as a general sketch of an action, i.e. a generalised motor program which is specified by a schema according to immediate task and environment demands [15]. It can also be seen as a unique entity, specific to particular movement patterns [7]. Recently, there has been a suggestion that motor programs consist of units that can be transferred to different contexts [10]. This modular view of motor program is in accord with the notion of action program being constituted by subroutines which were once simple programs [1,2,3]. The conceptual differences between action and motor programs turned out to be irrelevant since the latter were proposed to be a cognitive representation of the action [8]. The present study sought for further evidence on modularity in action programs. Claims for modularity need to be accompanied by predictions about the representational structure of the

program. A key to unravel such structure is to consider the evidence that movement patterns have invariant as well as variable features. The sequencing of events [9] and the relative timing [5,19] remain relatively constant in spite of changes, for instance, in the muscle selection or in the speed chosen to accomplish a given task [16]. Thus a program is hierarchically organized with invariant (at the macroscopic level) and variable (at the microscopic level) features [11,12]. If modular action programs were to exist they would not only expedite the learning of new tasks, as has been shown [10], they would have also to maintain some of its features invariant in the new skill. The adjustments required by the new task would be met by the module's variant features.

Graphic skills are suitable for this investigation as they are comprised by many stroke components that interact yielding a sequence representation which is a main feature of real world tasks [17]. Moreover, the individual strokes are likely to be important units controlled by a serial ordering mechanism [18]. Twenty four healthy young adults volunteered to take part in the study. They were university students who had been naive in regard to the experimental task. They had 100 trials (acquisition phase) to reproduce a letter (Fig. 1a) from the Chinese alphabet, completely

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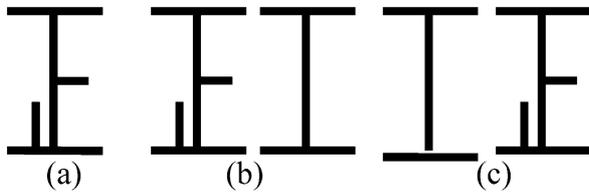


Fig. 1. Graphic patterns reproduce a letter from the Chinese alphabet. (a) Acquisition phase; (b) and (c) transfer and retention test (graphic patterns were reduced by 50%).

unknown to them, with the instruction of doing it as accurately as possible in each of the 20 squares equally distributed over an A4 size paper, from left to right. The instruction stated specifically that each stroke should have the start and end points well defined. This allowed the identification of the stroke sequences in the completion of the criterion figure. Any mistake should not be corrected. After the acquisition phase, the subjects were assigned to one of two groups for the transfer phase with 20 trials when both groups had to reproduce a more complex pattern composed by the criterion figure added with new stroke components. For Group A ($n = 12$), the new components were located to the right side of the criterion figure (Fig. 1b) whilst for Group B ($n = 12$) they were on the left side (Fig. 1c). The experimental design allowed a control for possible effects of the position of the figures due to constraints acting on the serial order of strokes known as ‘grammar of action’ [4]. The performance of each group in the first 100 trials served as a control for comparisons with their performance in the transfer phase. Next, there was an interval of 10 min followed by a retention test with 20 trials in which the same complex pattern had to be reproduced. This was a mean of disentangling temporary (performance) from long lasting (learning) practice effects. If the modular unit was transferred to the complex pattern the facilitative effects this had should still be present in the retention test.

Data acquisition was done with a digital tablet Quora Cordless QC-A4 (TDS Card-Graphics, England) with a wireless pen sensitive to pressure with a spatial resolution of approximately 0.05 mm at a sampling frequency of 100 Hz. Specially designed software for the acquisition and treatment of the data was developed in the Department of Psychology, Sheffield University, England. This software allowed the recording of spatial and temporal features of the subject’s graphic production plus the sequence of strokes chosen in each trial. A number of measures were taken to test specific questions. To evaluate learning and transfer effects we took the mean total movement time, obtained by the sum of movement times spent to complete each stroke and the mean total pause time, corresponding to the sum of intervals between one stroke and another. In both cases the results were collapsed into blocks of ten trials. Practice strokes became well defined in kinematic terms [20] leading to shorter times to complete them. The decrease of pause time indicates that decision making becomes optimised and

fluency of the whole action improves [14]. Hence, modularity warrants two possible results. First, mean total movement time and pause time spent to perform the criterion figure should decrease along the acquisition phase and must not increase in the transfer phase and retention test. Second, modularity implies that a unit keeps its identity in different contexts and tasks, thus invariant features should be less perturbed in the transfer phase and retention test. Likewise, the demands of greater complexity in the new pattern would be met by an increase of variability in the variant features of the programs. Invariant features were evaluated by measuring the mean variability (standard deviation) of relative timing of the strokes, the mean variability (standard deviation) of pause relative timing of the interval between strokes, and the variability of sequence of strokes. The latter measure was obtained by counting the number of times a different stroke was performed in a given order in ten trials. For instance, the criterion figure was composed of five strokes, if the subject repeated the same sequence in ten trials then an absolute value of one would be attributed to each position with a total of five. This number was subtracted from the number of strokes of the criterion figure (five) resulting zero, which means a very consistent performance. If, the subject modified one stroke in a given position in one trial, the sum after ten trials would be seven, which was then subtracted by five given a value of two for the variability of sequencing. The variable features considered in the present study were the mean variability (standard deviation) of total response time and of total pause time.

Total movement time and pause time decreased in the acquisition phase (Fig. 2). A series of one way ANOVAs run for each group found a significant difference in the total movement time for both groups, Group A $F_{9, 99} = 3.8266$, $P = 0.00032$ and Group B $F_{9, 99} = 7.8135$, $P = 0.0000$. Post-hoc Scheffé test failed to find the locus of the significant differences. For total pause time, a series of one way ANOVAs run for each group found a significant difference in Group A, $F_{9, 99} = 21.335$, $P = 0.000$, and Group B, $F_{9, 99} = 14.655$, $P = 0.0000$. Post-hoc Scheffé test found the locus of the significant differences only for Group A, between the first and second blocks of practice ($P = 0.0002$).

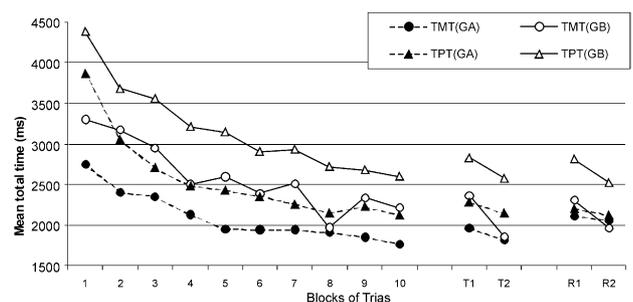


Fig. 2. Total movement time (TMT) and pause time (TPT) along acquisition (1–10), transfer (T1, T2) and retention (R1, R2) for Groups A (GA) and B (GB).

The first evidence for modularity was found after the conduction of a two way ANOVA, Group (2) × Block (5), with repeated measures in the last factor (last block of acquisition and two blocks of the transfer phase and the retention test). There was an interaction for total movement time, $F_{4, 88} = 2.9827$, $P = 0.023$. Post-hoc Scheffé test indicated that Group B had longer movement times in the first block of transfer phase in regard to the same variable for Group A. Total pause time had a statistically significant difference only for block factor, $F_{4, 88} = 3.1769$, $P = 0.0172$. A Tuckey post-hoc test detected a difference between the first block of the transfer phase and the last block of the retention test ($P = 0.0432$). This group difference indicates that the module was perturbed by the spatial configuration of the complex task. This may be due to a conflict of the grammar of action of the module and of the complex pattern. Nevertheless, the low impact of the new pattern on time to move and time to pause may indicate that the same program was used as a module in the more complex pattern. To check this possibility the invariant and variant features of the program were considered.

The variability of relative timing and relative pause time decreased in the acquisition phase (Fig. 3). Four one way ANOVAs (one for each group and measure) were conducted. In the relative timing, there was a significant difference for Group A, $F_{9, 99} = 2.290$, $P = 0.022$, with a post-hoc Scheffé test indicating a significant difference between Blocks 1 and 4 ($P = 0.0432$). In turn, Group B did not show any significant change, $F_{9, 99} = 1.669$, $P = 0.106$. In the relative pause time, Group A showed a significant change, $F_{9, 99} = 2.854$, $P = 0.0043$, with a post-hoc Scheffé test indicating a significant difference between Blocks 1 and 6 ($P = 0.029$). Group B also showed a significant change, $F_{9, 99} = 2.377$, $P = 0.017$, with a post-hoc Scheffé test indicating a significant difference between blocks 1 and 8 ($P = 0.016$). With the transfer there was a slight increase of variability in both measures but a series of two way ANOVAs, Group (2) × Block (5) with repeated measures in the last factor, showed only a block effect, $F_{4, 88} = 3.7212$, $P = 0.00769$ for relative timing and $F_{4, 88} = 4.3239$, $P = 0.00036$ for relative pause time. A post-hoc Scheffé test indicated a significant

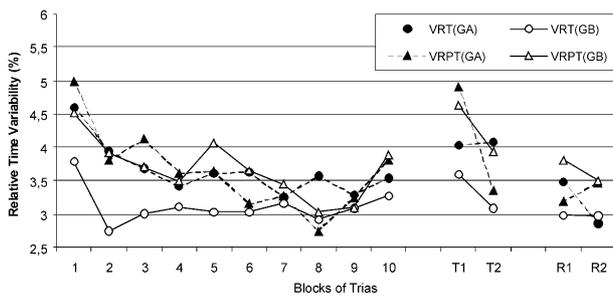


Fig. 3. Variability of relative timing (VRT) and relative pause time (VRPT) along acquisition (1–10), transfer (T1, T2) and retention (R1, R2) for Groups A (GA) and B (GB).

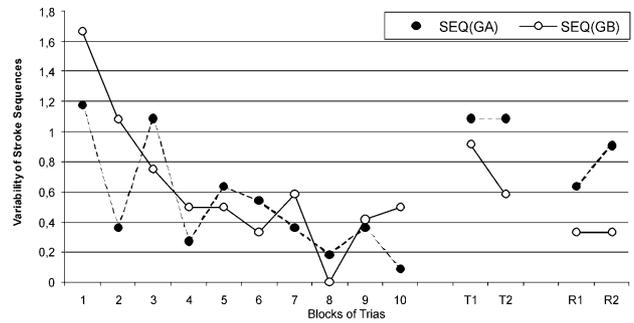


Fig. 4. Variability of sequencing along acquisition (1–10), transfer (T1, T2) and retention (R1, R2) for Groups A (GA) and B (GB).

decrease of variability from the first block of the transfer phase to the last block of the retention test for relative timing ($P = 0.01610$) and for relative pause time ($P = 0.0193$). These small effects are interesting though as they indicate the stability of the features that identify a program, i.e. relative timing and relative pause time, in the complex task.

A further indication of modularity was the variability of sequencing. It decreased after the first 20 trials for both groups (Fig. 4). The conduction of two Friedman’s one way ANOVAs for each group found a significant difference for Group A, $F_{9, 12} = 16.944$, $P = 0.049$ but failed to do so for Group B, $F_{9, 12} = 13.730$, $P = 0.132$. Post-hoc analysis also failed to locate the differences among blocks for Group A. In the more complex pattern, variability did increase for Group B whilst it remained close to zero for Group A. Again, no statistical difference was found following the conduction of two Friedman’s one way ANOVAs $F_{4, 11} = 5.514$, $P = 0.238$ for Group A and $F_{4, 11} = 1.513$, $P = 0.824$ for Group B.

Finally, variability of total movement time and total pause time decreased in the acquisition phase (Fig. 5). This was significant in the total movement time for Group A, $F_{9, 99} = 3.992$, $P = 0.000$ and Group B, $F_{9, 99} = 4.550$, $P = 0.000$. Post-hoc Scheffé tests found that in Group A, Block 1 was significantly different from Block 5 ($P = 0.030$) and in Group B, the significant difference was between Blocks 1 and 2 ($P = 0.000$). In the total pause time,

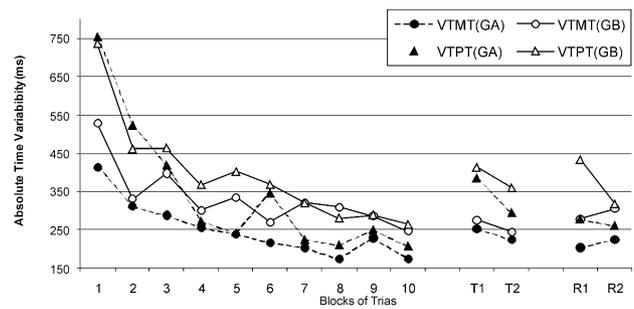


Fig. 5. Variability of total time movement (VTMT) and pause time (VTPT) along acquisition (1–10), transfer (T1, T2) and retention (R1, R2) for Groups A (GA) and B (GB).

Group A had a $F_{9,99} = 7.809$, $P = 0.000$ and Group B had a $F_{9,99} = 6.266$, $P = 0.0001$. Post-hoc Scheffé tests indicated significant differences between Blocks 1 and 3 ($P = 0.011$) for Group A, and between Blocks 1 and 2 ($P = 0.0235$) for Group B. A series of two way ANOVAs, Group (2) \times Block (5), with repeated measures in the last factor did not detect significant differences from the acquisition phase to the transfer phase and retention test.

Positive transfer is an important evidence for modularity of action programs. Hence, the present study corroborates recent results favourable to modularity [10]. However, positive transfer alone does not give enough evidence for a module. Here we went one step further proposing a hierarchical organization for a module and finding evidence for its stability at the macroscopic level, i.e. its invariant features in the more complex pattern. This is important to show what might be the representational structure of the action program. Some of these features corresponded to recent findings [9]. Acquisition may involve the formation of modules that are then stored and selected in a hierarchical fashion to form more complex patterns. Group differences suggest that the grammar of action may perturb the module thus different pattern configuration should be tried in new studies. Moreover, the developmental status of the subjects should also be manipulated as modularity of action may be a particularly relevant strategy for younger and more immature drawers to deal with novel tasks.

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