Chunking Patterns Reflect Effector-dependent Representation of Motor Sequence

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Abstract

Sequential organization is central to much of human intelligent behavior ranging from everyday skills such as lacing shoes to using a computer. It is well known that such sequential skills involve chaining a number of primitive actions together.. A robust representation of skills can be formed by chunking together several elements of a sequence. We demonstrate, using a 2x6 finger movement task, that during the process of acquiring visuomotor skills the chunking patterns remained unaltered when utilizing an effector dependent representation of the sequence. In the 2x6 task, subjects learned a sequence of 12 visual cues displayed as six sets of two elements each and performed finger movements on a keypad.Two experiments Normal-Motor and Normal-Visual were conducted on nine subjects and two observations were collected from each subject. Each experiment consisted of a *Normal* and a *Rotated* condition. In the *Rotated* (*Motor* and *Visual*) conditions, subjects were required to rotate the visual cues by 180 degrees and press the corresponding keys. The display sequence was also rotated for the *Motor* condition, requiring an identical set of effector movements to be performed as in the *Normal* condition. Chunking patterns were identified using the response times (RTs) for individual sets of the sequence. A pause between set RTs demarcates an ensuing chunk. We demonstrate that usage of an effector dependent representation is supported by the observation of identical chunking patterns between the *Normal* and *Motor* conditions, and the lack of similarity in chunking patterns between the *Normal* and *Visual* conditions.

Motivation

A variety of day-to-day tasks such as lacing shoes, riding a bicycle and using a computer involve sequencing a number of primitive actions to achieve a desired goal. Lashley (1951) highlighted the ubiquity of sequential nature or serial order in our behavior

> "...the coordination of leg movements in insects, the song of birds, the control of trotting and pacing in a gaited horse, the rat running the maze, the architect designing a house, the carpenter sawing a board present a problem of sequences of action ..."

It is well known that the human brain clusters the amount of available information into a number of chunks. When we recall a mobile phone number such as 9440746382, we might actually chunk this sequence as 94407 46 382, or as 944 07 463 82. Miller (1956) suggested that the capacity of short-term working memory is roughly 7 ± 2 chunks. Sakai, Kitaguchi, and Hikosaka (2003) have shown that the performance of a shuffled sequence deteriorated when the chunk patterns of the original sequence were compromised than when they were preserved. Thus each chunk is processed as a single memory unit. Bapi, Pammi, Miyapuram, and Ahmed (2005) have suggested that hierarchically organizing sequences into chunks enables efficient retrieval compared to linear representation of sequences. Pammi, Miyapuram, Bapi, and Doya (2004) have shown that greater reorganization of sequences into chunks is more likely when the amount of information to be processed at a time is kept smaller, well within the capacity of short term memory.

Fitts (1964) proposed that acquisition of a skill involves transition from an initial, attentive phase to an automatic phase after repeated practice. In an earlier behavioral study ((Bapi, Doya, & Harner, 2000)), we investigated transfer effects in a modified $m \times n$ motor sequence learning paradigm (Hikosaka, Rand, Miyachi, & Miyashita, 1995). Further, we demonstrated that sequence learning is mediated by an effector-independent, visuo-spatial representation in the early phase and an effector-dependent, motor representation enables efficient performance in the late phase. Sakai et al. (2003) have also found that the temporal patterns of sequence performance transferred from the non-dominant to dominant hand, but not vice versa. In this context, it is interesting to investigate if the chunking patterns are effector dependent or not.

Experimental Procedures

In the current experiment, subjects are presented with a series of visual stimuli on a display grid. They discover the correct sequence of key presses on a keypad corresponding to the visual stimuli by trial and error. In the 2×6 task, two squares (called a *set*) are illuminated simultaneously on a 3×3 display grid. Subjects are required to press two corresponding keys successively on a keypad. Upon successful completion of a *set*, the next *set* is presented and so on. The entire se-

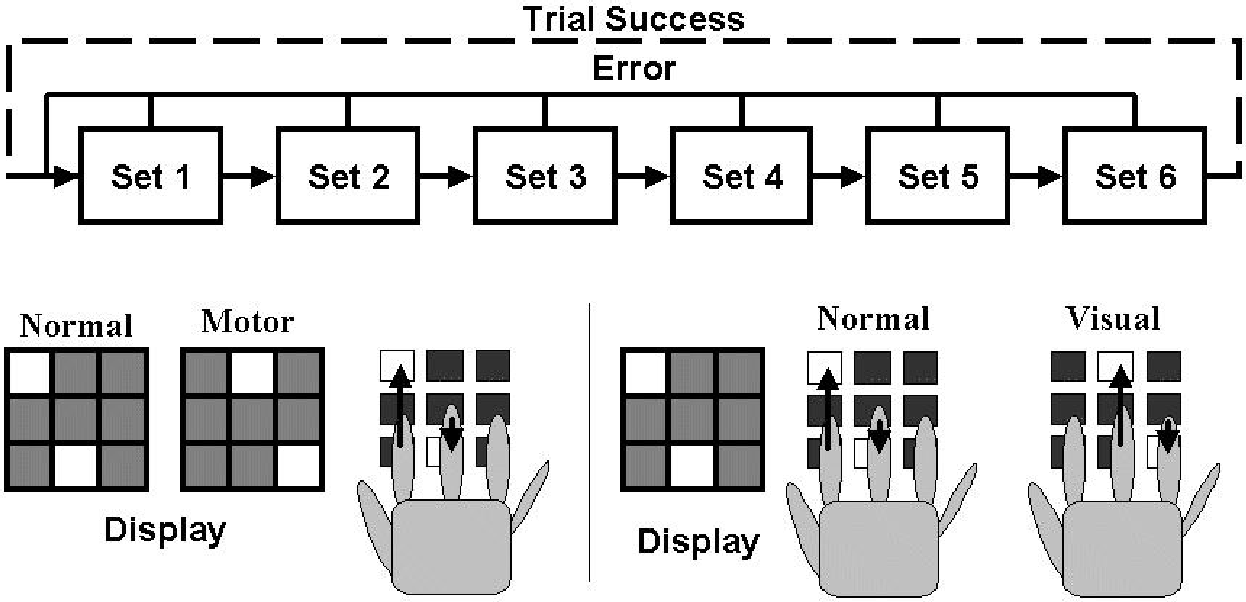

Figure 1: 2x6 Trial and Error Learning Task (Top panel). One set of the sequence for Normal-Motor experiment is shown on left side of bottom panel and the Normal-Visual experiment is shown on the right side. The display to keypad rotation was 180 for both the Motor and Visual Rotated Settings.

quence to be learnt consists of six such *sets* and is called a *hyperset*. The trial was reset to the beginning of the *hyperset* (sequence) upon error. Subjects repeatedly practiced the same sequence upon trial success (see Figure 1 top panel). Each subject used a different sequence. Hence our results are not specific to any sequence. Further we avoided any repetition or transposition of sets within a hyperset to avoid any effects due to the physical structure of the sequence. Sakai et al. (2003) have used similar strategy to show that subjects spontaneously chunk a sequence and that the chunking was not specified by external parameters of the sequence. Sakai et al. (2003) have tested effector dependence by testing transfer across hand, while in our study, we address this question by rotating either the display sequence or the effector movements. Further, unlike Sakai et al. (2003) in which subjects performed the sequence with their index finger only, we asked subjects to align their index, middle and ring fingers to the three (left, middle and right) columns of the keypad respectively to minimize any additional arm movements, thus reducing the movement times.

Nine subjects participated on two experiments using two different sequences. Subjects repeated the two experiments on a different day using another pair of sequences. In one experiment, Normal-Motor, subjects learned to perform the same sequence of finger movements in response to a *Normal* and a 180° Rotated display (Figure 1, bottom left panel). In the second experiment, Normal-Visual, subjects were shown identical visual stimuli, but were required to generate two sequences (*Normal* and 180° Rotated) of finger movements (Figure 1, bottom right panel). While in the normal setting the display and keypad were arranged in the usual upright position, the display-to-keypad rotation was 180° for the *Rotated* (*Motor* or *Visual*) conditions. Thus, in both the *Rotated* conditions, subjects have to mentally rotate the presented pattern to generate the motor response. The difference between the two rotated conditions was that in the *Motor* condition subjects use same effector movements as in the *Normal* using a different display sequence, while in the *Visual* condition subjects use a different sequence of effector movements keeping the display sequence same as that of *Normal*.

Subjects used different hypersets for the two experiments (Normal-Motor and Normal-Visual) and for the two repetitions to prevent any transfer of sequence knowledge from one experiment to another. We hypothesized that if chunking of visuomotor sequences is mediated by effector dependent representation (i.e., in motor coordinates, say, in the finger/arm coordinates), then patterns of chunking with the keypad-hand conditions that retain the effector (finger) movements (such as the *Normal* and *Motor*) should be similar, while they would be different between the conditions that do not preserve effector movements (*Normal* and *Visual*).

In our previous behavioral study (Bapi et al., 2000) using a similar paradigm, training was given in the normal condition and sequence recall was assessed during test blocks in rotated settings. In the current experiment subjects alternated between *Normal* and *Rotated* conditions for a total of 18 blocks of 36 seconds each, thus measuring the progress of learning in the rotated conditions at different stages. We assume that the chunking patterns would have stabilized by the late stage of learning and hence discuss the results from the last six blocks of these experiments. Sakai et al. (2003) have used the errors in the early stage of learning to predict the chunking patterns. As the main focus of the paper is to investigate the effector dependence of chunking patterns, we present the relevant correlational analysis and the corresponding results.

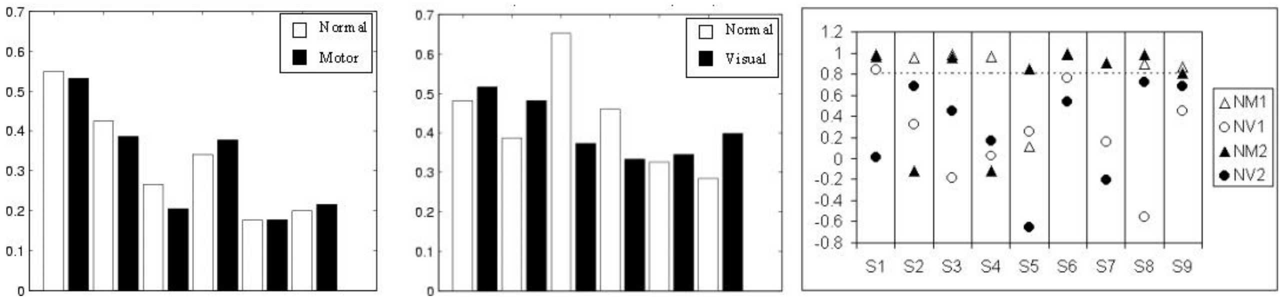

Figure 2: Correlation between Normal and Rotated Settings. The bar graphs show the average response times (sec) for each of the six sets in the sequence for one pair of experiments. The dot plot on the right shows the correlation coefficient for all the nine subjects and two repetitions. The dashed line indicates the critical value of pearson correlation coefficient (R) for p=0.05 with 4 degrees of freedom.

Results

To identify the chunking pattern, we extracted the response times for individual sets for all successful trials in the last six blocks of each experiment. The average values of these response times gives the temporal profile corresponding to chunking of the sequence. Significant pauses between response times for individual sets within the sequence were used to mark the beginning of a chunk. The chunking pattern was determined for the *Normal* and *Rotated* condition for each experiment separately for all subjects.

Figure 2 (left and middle panels) shows the chunking patterns for the two experiments for a representative subject. It was observed that chunking patterns were similar for the *Normal* and *Motor* conditions, while those in *Normal* and *Visual* condition differed. In the Normal-Motor experiments, the chunking pattern was first three sets as one chunk and then the next three sets as the second chunk in both the *Normal* and *Rotated* conditions as revealed by the pause between the third and fourth sets (see, Fig. 2 left panel). However, in the Normal-Visual experiments, the chunking pattern was first two and last four sets for the *Normal* condition, which is clearly not the case for the *Visual* condition (see, Fig. 2 middle panel). As subjects used different hypersets in the Normal-Motor and Normal-Visual experiments, the chunking patterns cannot be compared across the two experiments.

We then tested for the similarity of the chunking pattern between the *Normal* and corresponding *Rotated* condition for each experiment (Normal-Motor and Normal-Visual) by computing the correlation coefficient and its two-tailed significance. Figure 2 (right panel) depicts the correlation coefficients for all the subjects which clearly demonstrate that in 15 out of 18 experiments a significant correlation between the *Normal* and *Motor* conditions was observed. On the other hand, 17 out of 18 experiments had lacked a significant correlation between the *Normal* and *Visual* conditions.

These results suggest that chunking patterns are similar across conditions that use similar effector movements inspite of using different visual guidance cues. Further more, the chunking patterns are different when the effector movements were different although the visuo-spatial cues remained unaltered. We thus conclude that chunking patterns reflect the motor sequence representation and that these are effector-dependent.

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