The effect of behavioral interference on the kinematics of a movement sequence during learning

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BACKGROUND - MOTOR SEQUENCE LEARNING

Sequence A: 4, 1, 3, 2, 4
Sequence B: 4, 2, 3, 1, 4
**BACKGROUND - POWER LAW**

Power law: $T = N^{-\beta}$

$N$ = number of practice trials

$\beta$ = learning rate
BACKGROUND - POWER LAW

- Power law: $T = N^{-\beta}$
- Exponential: $T = e^{-\alpha N}$
- $N =$ number trials, $\alpha$ or $\beta$ are the learning rate
- Power law implies reduction in learning rate with practice
- Exponential implies constant relative rate of learning (Heathcote et al., 2000)
SLOW AND FAST LEARNING

- Studies have highlighted the importance of time and not only the number of trials in learning (e.g. Karni et al., 1998)
- There are two broad types of learning observed:
  - Fast, within-session learning
  - Slow, between-session learning
- Both are experience-dependent
Fast learning occurs within a training session
There is a habituation effect
SLOW LEARNING

- Slow learning occurs between training sessions
- It is dependent on sleep
- It involves changes in the representation of the sequence in the motor cortex (M1)
One way that the representation could be changed is by “chunking”

There is where lower-level primitives are combined in a hierarchical way (e.g. Sosnik et al., 2004)
CHUNKING
Ways of manipulating practice

- There are several ways of performing training that are known to affect learning performance. These include:
  - sleep
  - augmented feedback
  - massed practice
CONSOLIDATION AND INTERFERENCE

- Consolidation occurs a few hours after practice, where skills are processed, changed and strengthened in memory.
- Consolidation refers to:
  - Improvement in the skill off-line, between practice sessions.
  - Increase in stability of memory resulting from training making it no longer susceptible to interference.
- Both aspects of consolidation can be measured in the lab using motor skill learning.
- The consolidation process can be interfered in most subjects.
- One way of doing this is learning a similar sequence 30-90 minutes after learning the initial sequence.
In the finger opposition task, subjects are required to make many decisions about how to perform the sequence. The task is redundant at many levels, i.e. there are many ways to perform the task, for example:

- contribution of the fingers vs. the thumb to the movement
- magnitude of the finger movements
- relative timing
- posture of the hand
VARIANCE AND LEARNING

- In addition, there is variability inherent in any movement
- Source of variability include:
  - noisy and delayed sensory feedback
  - noisy motor commands
  - variable relationship between motor command and outcome, due to the environment
VARIANCE AND LEARNING

- With motor learning, the amount of variance is reduced
- However, at early stages of motor learning, exploration of solutions is useful for improving learning
- Recent studies (e.g. Wu et al., Nature Neuroscience 2014) have shown that higher levels of task-relevant motor variability predict motor learning ability
- This corresponds with the notions of action exploration, from reinforcement learning, i.e. variability is regulated to improve learning
GOALS OF THE STUDY

There were several goals for this study:

- How, in terms of kinematics, did subjects improve their performance?
- What is the effect of interference on behavioral measures (number of sequences) and kinematic measures?
- Can we predict learning outcomes from early variability?
Methods

- We used the sequence production task used in many previous studies
- Right handed subjects touch the fingertip with the thumb of the left hand in a specified order (4-1-3-2-4)
• We recorded the trajectories of the fingertips using a magnetic motion capture system (Polhemus Liberty) at 240 Hz
Two groups:
- No-interference group: Performed pre-test, training, post-test and 24 hr tests
- Interference group: In addition, 30-90 minutes after the pre-test, the subjects learned another sequence (4-3-2-1-4)
DECOMPOSITION OF IMPROVEMENT

- Increase performance
- Decrease movement duration
- Reduce gaps between movements
- Increase velocity
- Decrease amplitude
- Reduce gaps between sets
- Reduce gaps within sets
DATA ANALYSIS

- Analyze the behavioral data - number of sequences, number of error
- Decompose the improvement as described
- Improvement is defined as the relative difference compared to the first test:

\[ I_j = \frac{S_j - S_1}{S_1} = \frac{S_j}{S_1} - 1 = \frac{D}{T_j} = \frac{T_1}{T_j} - 1 \]

\[ I_j = \text{improvement}, \ S_j = \text{number of sequences}, \ D = \text{time available (30 seconds)}, \ T_j = \text{average time taken} \]
DATA ANALYSIS

- The time taken for each sequence can be divided into the time for the movements \( t_{mj} \) and the gap \( t_{gj} \)

\[
T_j = t_{mj} + t_{gj}
\]

- The improvement can then be decomposed into the part due to reduction in movement time \( I_{mj} \) and the reduction in gaps \( I_{gj} \):

\[
I_{mj} = \frac{t_{m1} - t_{mj}}{T_j}
\]

\[
I_{gj} = \frac{t_{g1} - t_{gj}}{T_j}
\]

- We note that the time for the gaps can become negative (due to coarticulation)
The improvement in movement time can be further decomposed into a reduction of the amplitude or an increase in the peak velocity

\[ I_{pj} = \frac{t_{m1} \left(1 - \frac{P_j}{P_1}\right)}{T_j} \]

\[ I_{aj} = \frac{t_{m1} \left(1 - \frac{A_1}{A_j}\right)}{T_j} \]

\( P_j \) is the peak velocity, \( A_j \) is the amplitude
SAMPLE MOVEMENTS
Both training protocols resulted in significant improvements during training.

There was significant consolidation only for the no-interference group.
**DECOMPOSITION OF SEQUENCE TIME**

- Movement time is initially about $\frac{1}{3}$ of the sequence time
- While the gap times decrease, there is almost no change in the movement time
Most of the improvement came from reduction in the gaps
Gaps within sequences accounted for more improvement than gaps between sequences
## RESULTS - IMPROVEMENT IN MOVEMENT TIME

<table>
<thead>
<tr>
<th>Improvement</th>
<th>Peak Velocity</th>
<th>Movement Time</th>
<th>Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>A pre</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A post</td>
<td>−0.2</td>
<td>0</td>
<td>0.2</td>
</tr>
<tr>
<td>A 24 h</td>
<td>0</td>
<td>0.2</td>
<td>−0.2</td>
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<tr>
<td>B 24 h</td>
<td>0.2</td>
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<tr>
<td>B RH 24 h</td>
<td>0</td>
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<td>0.2</td>
</tr>
<tr>
<td>A RH 24 h</td>
<td></td>
<td></td>
<td>−0.2</td>
</tr>
</tbody>
</table>

- Overall, there is almost no change in overall performance due to changes in movement
- Decomposing the improvement into velocity and amplitude shows significant changes
- In general, the peak velocity increased
- The amplitude also increased (i.e., negative improvement)
- These two effects approximately canceled out
The novelty effect is quantified by the slope of performance within the 4 repetitions of a test / re-test. If the sequence is novel, performance will likely improve significantly (i.e. large slope). If it is not novel, the improvement (slope) will be small. The second sequence was not novel for the interference group, showing that they did learn the second sequence.
Does variance predict improvement?

- Often the standard deviation increases approximately linearly with the mean for movement-related measures.
- This may cause spurious correlations to occur if we compare standard deviation to the mean.
- Instead, we will use the coefficient of variation (CV), which is the standard deviation divided by the mean.

\[ cv = \frac{\sigma}{\mu} \]
DOES VARIANCE PREDICT IMPROVEMENT?

\[ R^2 = 0.3038, \ p = 0.0007 \]

\[ R^2 = 0.0135, \ p = 0.5123 \]

\[ R^2 = 0.0080, \ p = 0.6158 \]

\[ R^2 = 0.0476, \ p = 0.2152 \]
DOES VARIANCE PREDICT IMPROVEMENT?

- We observe that the CV of movement time in the first pre-test (30 s) predicts the improvement in sequence time and gap times at post-test and at 24 hr.
- There is a small negative correlation of movement time improvement with movement time CV.
- The CV of gap time or sequence time does not predict improvement.
- The CV predicts improvement at post-test or 24 hr, but not the consolidation change.
WHAT DOES PREDICT CONSOLIDATION IMPROVEMENT?

▶ Does improvement in the first session predict the amount of improvement with consolidation?
▶ We found that only the improvement in gap times within a session predicts consolidation improvement of sequence time, but only for the no-interference group
▶ No other correlations were significant
WHAT DOES PREDICT CONSOLIDATION IMPROVEMENT?

- Improv. MT
  0.8
  1
  1.2
  1.4
- Improv. gaps within
  1
  2
  3
  4
  5
- Improv. gaps between
  -0.01 0 0.01 0.02 0.03...
- MT impr pre
- Improv. sequence time
- Gap times impr within pre
- Gap times impr between pre
- Sequence time impr pre

No interference
Interference
As expected, learning a second sequence shortly after the first interfered with the consolidation of the first sequence. The effects of interference were not the same for all aspects of the movement. The abstract, organization driven process of determining the gaps between movements was affected by interference. The sensory feedback driven timing of individual movements was not affected by interference. An absence of change in movement time does not mean learning did not take place in terms of the movement itself. Rather, robust changes were seen in terms of the movements, but the changes in velocity and amplitude were masked.
While movement time did not show large changes with learning, the CV of movement time in the first 30s pre-test predicted the improvement during fast learning (on the first day)

CV of MT did not predict consolidation gains

The improvement in gaps did predict the consolidation gains for the no-interference group
CONCLUSIONS

- Interference is naturally present in almost any ecological setting (e.g. sensory distractors, competing experiences)
- Their influence should be considered in the time course of learning in typical and clinical populations
- We note that the effect of interference differs depending on the type of learning
- Optimization of timing of motor components seems to be affected by interference
- Biomechanical or sensory-feedback related optimization is likely to be interference immune
- Variance during some aspects of training are correlated with the amount of improvement. It is currently unknown if artificially increasing variance will lead to greater improvement
THANKS

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