# Intermittent control in human motor control

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Sackler Faculty of Medicine

Sagol School of Neuroscience

# Recruiting a PhD student

I am recruiting a PhD student for a project on enhancing motor learning (of the piano and swimming) using computational scaffolding. Students with a background in human motor control, Physical Therapy, Neuroscience, Psychology, Physics, Computer Science, Biomedical engineering or related areas are encouraged to apply.

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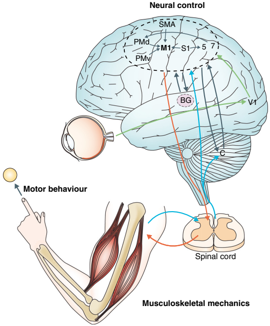
www.movementscienceslab.com/join-us

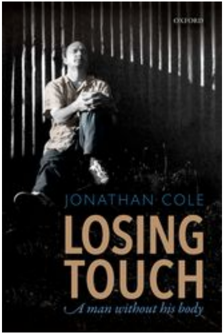
# MUSCLES AND THE BRAIN

- Our movements are generated by our muscles
- Our muscles are controlled by the central nervous system



# Muscles and the brain

- Our movements are dependent on feedback
- Without feedback, it is very difficult to move!
- e.g. Ian Waterman, the man who lost his body



# MUSCLES AND THE BRAIN

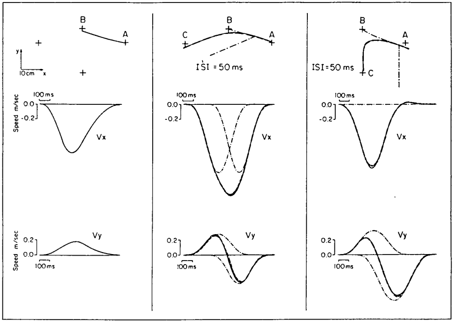
- The problem with using feedback is that it is slow!
- Depending on the modality, the feedback loop is in the order of 100-200 ms
- There are also delays in the response of the limbs, as muscles take time to develop force and act like low pass filters
- So how do we deal with the need for feedback, when feedback is so slow?

# Intermittent control

- One possible solution is the use of intermittent control
- Rather than continuously controlling movement, motor commands are given at discrete times
- This simplifies movement planning, and makes the system more stable given slow feedback

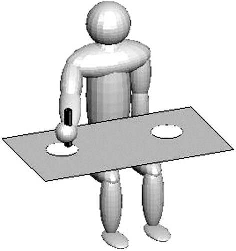
# SUBMOVEMENTS

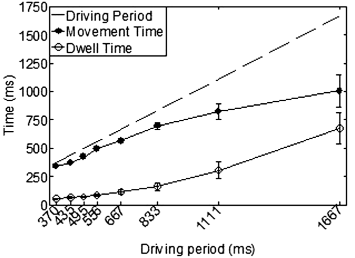
- The primitives of movement are often called submovements - e.g. straight line movements with bell-shaped velocity profiles
- More complex movements can be constructed by combining multiple submovements (Flash & Henis, 1991)



# SLOW MOVEMENTS

- We have difficulty in making slow, smooth movements
- Other animals seem capable of making slow movements, e.g. sloths
- When instructed to make slow movements, people will often cheat if they can (van der Wel, Sternad & Rosenbaum, 2010)

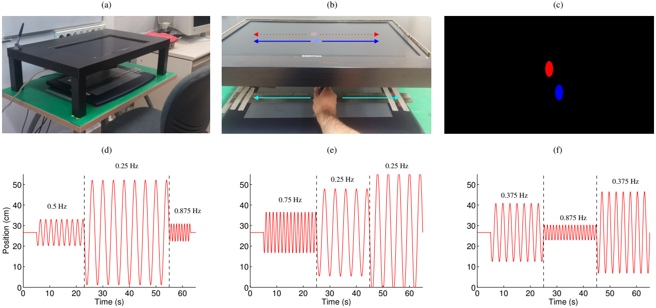




# Why can't we produce slow and smooth movements?

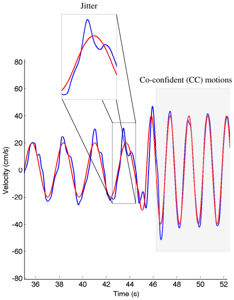
- Skilled point-to-point movements consist of a single velocity peak
- However, there are limits to our performance
- What happens when we make very slow movements?
- Will a perfectly planned, slow movement show a single velocity peak?

# Experimental setup




- We used a one-person version of the mirror game
- The subject moves a stylus left-right to move a blue ellipse, and tries to match the location of a red ellipse moving on the screen
- A range of movement frequencies and amplitudes (velocities) were selected

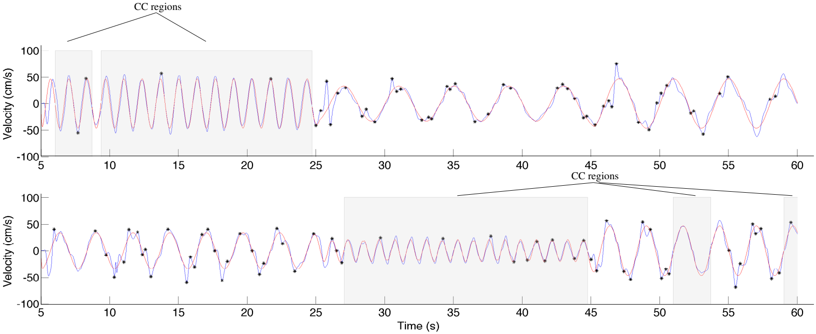
# Extraction of jitter / calculation of co-confident (CC) motion




- Based on previous studies (Noy et al.,2011), we used jitter (similar to acceleration zero crossings - AZC) as a measure of smoothness.
- We then looked for regions of movement where there is no unnecessary jitter (AZC) and accuracy is high, these are termed co-confident motion (CC)

# Dependence of CC on movement frequency

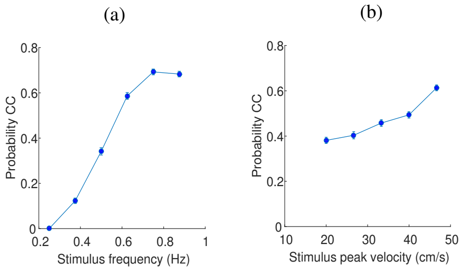
## Noy, Weiser & Friedman, 2017. Front. Psych




- Periods of CC motion were strongly dependent on the movement duration

# CC PROBABILITY IS A FUNCTION OF MOVEMENT FREQUENCY

NOY, WEISER & FRIEDMAN, 2017. FRONT. PSYCH




- CC probability was strongly dependent on movement frequency (i.e. duration)
- i.e. Subjects were unable to perform smooth, low frequency movements
- Movement speed had little effect

# WHAT ARE THE REAL LIMITS OF PERFORMANCE?

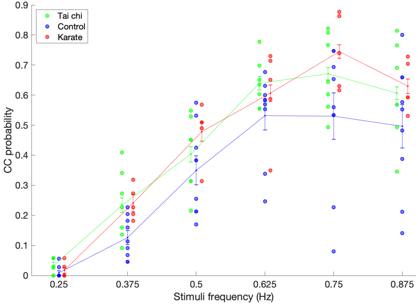
- What is limiting slow, smooth movements?
  - Lack of familiarity (motor primitives)?
  - Inertial properties of the limbs (natural frequency)?
  - Biomechanical constraints (motor units, etc.)?
  - Tremor?

# Preliminary results - experts

- We compared experts in slow movement (Tai Chi practitioners with $>$ 10 years experience) to a control group of Karate practitioners

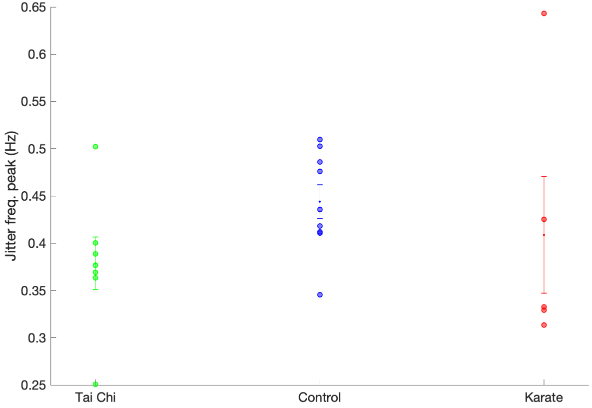
# PRELIMINARY RESULTS - EXPERTS (TAI CHI)

- Expert Tai Chi practioners (> 10 years experience) can (better) produce slow, smooth movements



# Preliminary results - experts (Tai Chi)

- This difference is also observed in terms of the jitter frequency (i.e. how often they correct their movements)



# INTERIM SUMMARY

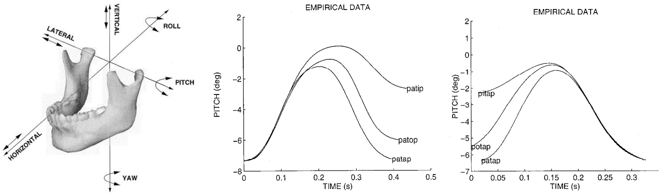
- Part of our inability to perform slow, smooth movements appears to come from a lack of movement primitives for slow, smooth movements
- This may be because of a lack of practice in day-to-day life - usually when we want to move, we make relatively fast movements
- We may need to generate new movements primitives in order to allow us to produce slow, smooth movements
- There is still clearly a lower limit in terms of movement speed (for smooth movements), but it is unclear what is the limiting factor

# MOTOR LEARNING

- Motor learning is the process of learning to perform a task in a qualitatively better way
- Complex movements may be constructed from the combination of a number of motor primitives
- Motor learning can then involve the generation of new motor primitives, and/or changes in the way motor primitives are combined

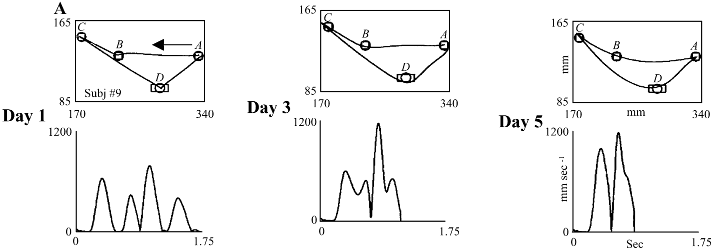
# COARTICULATION

- Some types of movements are difficult and / or time consuming to learn
- An example of this is movements that require coarticulation
- Coarticulation is a term used in speech production, where the articulator movements for a given sound depend on surrounding sounds (Ostry et al. 1996 J. Neurosci.)



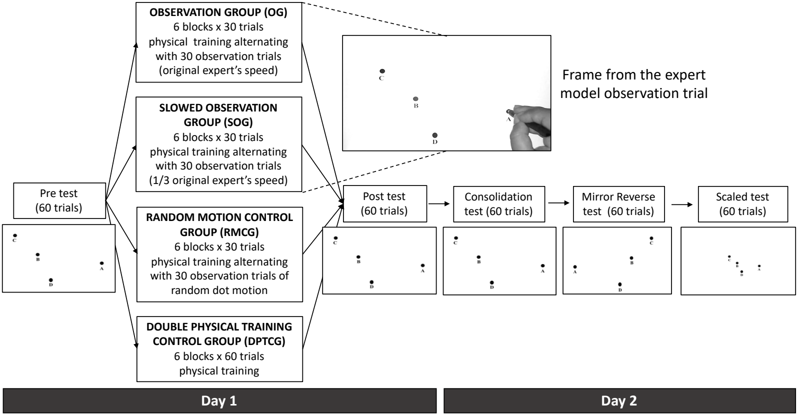
# COARTICULATION

- A previous study (Sosnik et al., 2004) showed that subjects require multiple days to qualitatively improve in a drawing task involving connecting multiple dots

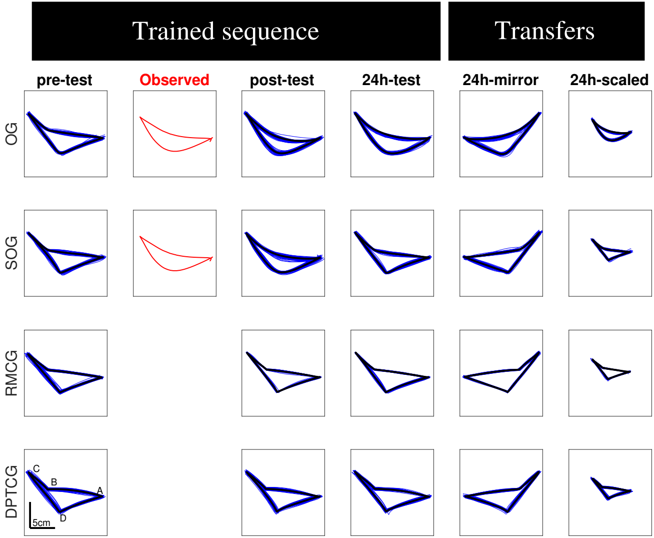



- They suggested that a new motion "primitive" is only learned after the system has reached optimal performance
- We tested whether learning by observation can enable faster learning of this skill

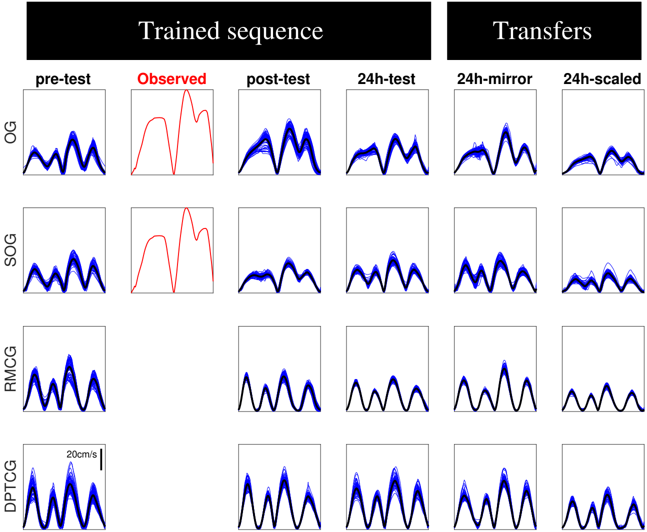
# EXPERIMENTAL PROTOCOL



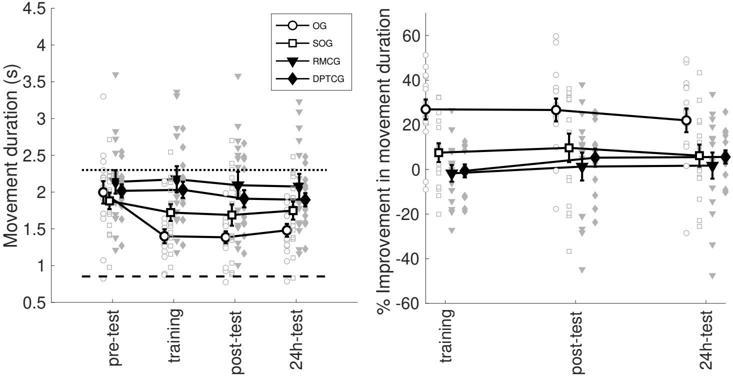
# Results - trajectories



# Results - tangential velocity profiles



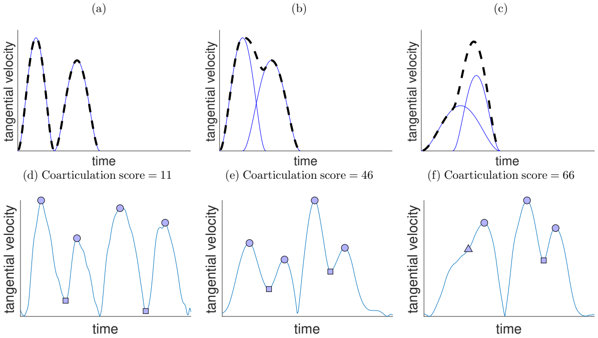
# Results - movement duration



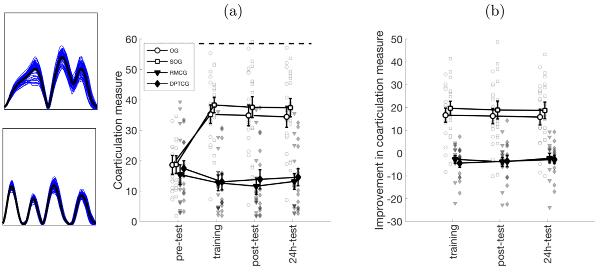

- Movement time decreased almost instantaneously only for the observation groups
- This improvement was maintained even after they stopped observing the sequence, and after 24 hours

# Coarticulation measure

- Coarticulation enables faster task performance, i.e. they overlap production of "submovements"
- We defined a coarticulation score to quantify this: ratio of the height of the troughs to the peaks in the tangential velocity profile, times 100

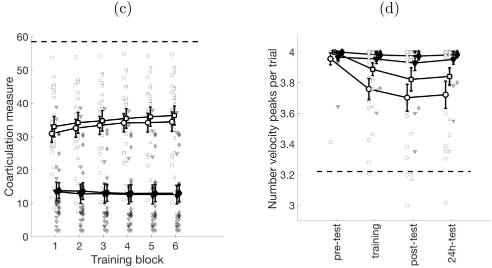


# RESULTS - COARTICULATION MEASURE




- Large, instant differences are observed in terms of the coarticulation measure
- i.e., the participants are not just moving faster, but also changing the spatial aspects of the movement

# Results - coarticulation measure




- The observation groups continue to improve during the training, after the step-wise increase
- They did not, however, reach the level of the expert - likely because they used the same primitives rather than generating new primitives

# Interim Summary

- Observation of an expert model induced an instant, robust improvement in performance - a Eureka moment
- The improvement remained at post-training and 24 hr
- Despite the large amount of improvement, new kinematic primitives were not produced
- Observation of hand movements of an expert model coaligned with self-produced movements during training can significantly condense the time-course of ecologically relevant drawing / writing skill mastery.

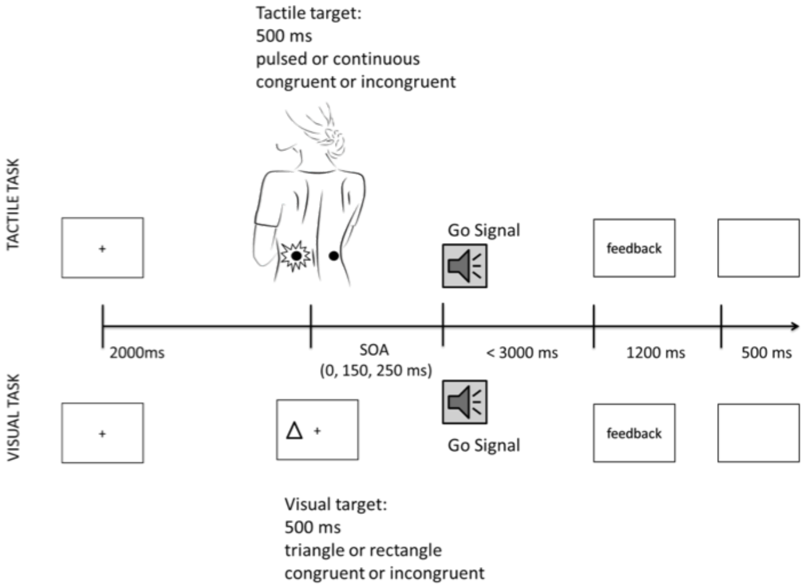
# Background - response times (RT)

- Response times (RT) are the typical way to study the Simon task
- Reaction times measure the end of the decision making process, and require us to infer what is going on during the decision making
- Ideally we would like a way to probe the ongoing decision process

# Arm movement studies

- Arm pointing movements are useful because:
  - They are natural responses
  - They take long enough that you can change your mind during the movement
  - We can force people to start moving before they make their final decision

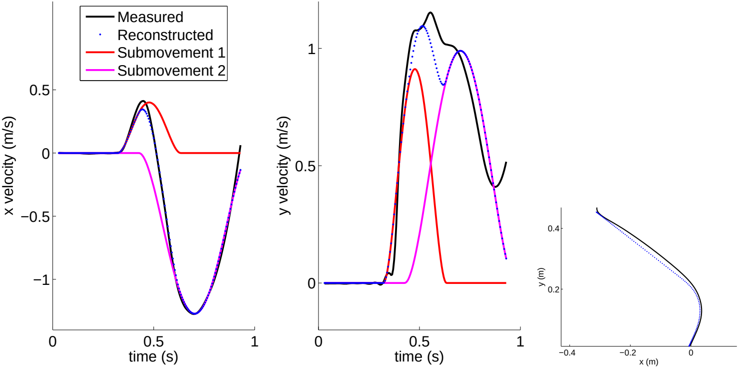
# METHODS


Tactile target:
500 ms
pulsed or continuous
congruent or incongruent
TACTILE TASK
Go Signal
feedback
2000ms
SOA
(0, 150, 250 ms)
< 3000 ms
1200 ms
500 ms
VISUAL TASK
Go Signal
feedback
Visual target:
500 ms
triangle or rectangle
congruent or incongruent

# SUBMOVEMENT DECOMPOSITION

- Rather than working with the whole trajectory, we decompose the movement into *submovements* - discrete, stereotypical movements that are serially concatenated and overlapping in time
- They are *discrete* rather than continuous at the planning stage, and planned in a feed-forward manner (i.e., they reflect intermittent control)
- This means that all the properties of a submovement are proscribed at the start of the movement (e.g. amplitude, direction, timing)

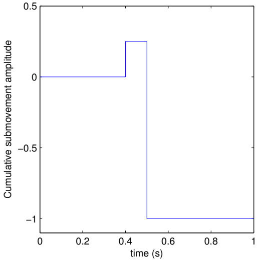
# SUBMOVEMENT DECOMPOSITION - EXAMPLE



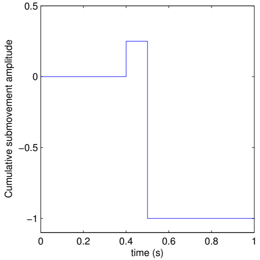

- This method gives the onset times $T_0$ and amplitudes $D_x$,$D_y$ of the submovements, which are a compact description of *intent* at a specific time.

# Cumulative submovement amplitude

- We use cumulative submovement amplitude (e.g. Finkbeiner & Friedman, 2011) as a proxy for the decision making process
- We look only at the left-right planned amplitudes of the submovements



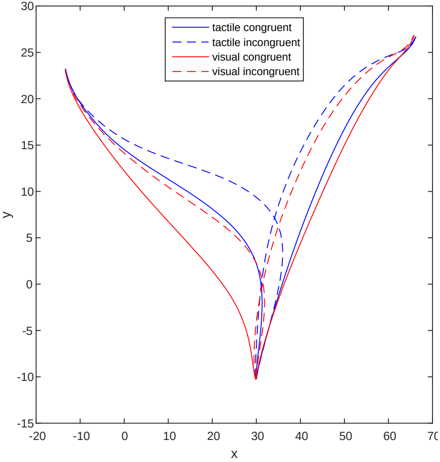
# Cumulative submovement amplitude



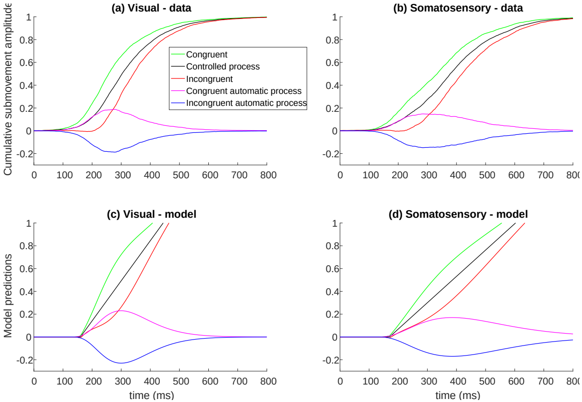

- The cumulative submovement amplitude is a measure of intent - when it is 1 or -1, the subject has made a decision.
- When it is between -1 and 1, the subject has not yet made a final choice, but the value reflects the decision making process and biases

# Results - trajectories

Congruent and incongruent movements show different trajectories, as do visual and tactile



# RESULTS - CUMULATIVE SUBMOVEMENT AMPLITUDE




- Cumulative submovement amplitude allows us to decompose the movements into two processes - an automatic and a controlled
- We are then able to accurately model these movements and understand these component cognitive processes

# Interim Conclusions

- Using arm movements provides further insights into the temporal dynamics of decision making processes
- In particular, in situations with conflict we can extract the temporal dynamics of the multiple processes

# CONCLUSIONS - INTERMITTENT CONTROL

- Intermittent control provides a framework for studying multiple questions in human motor control, including
  - movement production
  - motor learning
  - decision making
- It is also a useful tool when studying, analzying and modeling
  - Rehabilitation
  - Development
- Intermittent control presents a potential solution to explain our ability to make exquisite dexterous movements despite our slow feedback loops

# Thanks

- Neta Weiser (Tel Aviv University)
- Lior Noy (IDC Herzliya)
- Maria Korman (University of Haifa)
- Yael Salzer (Volcani Center)

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