Using arm movements to understand decision making, and vice-versa

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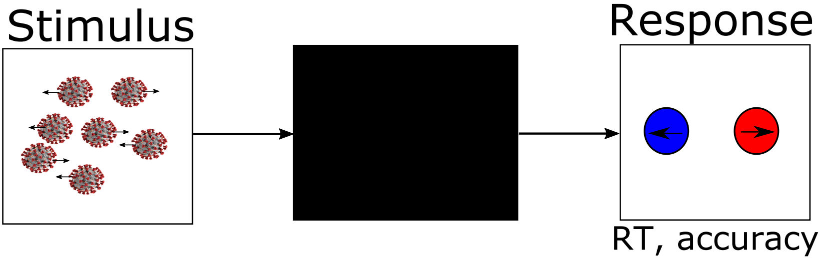
DECISION MAKING

- We are constantly making decisions
- These range from very fast perceptual decisions (e.g. is the light red?) to more complicated decisions (should I wake up at 4am to give a talk via zoom)
- In this talk, the focus is on fast perceptual decisions (<1500 ms)

Decision making

- Decision making is a widely studied topic because it gives us a way of studying many cognitive processes
- All decisions, even those which seem extremely simple, are the result of a process
- Modelling the temporal dynamics of these processes can help us understand how the brain processes different types of information

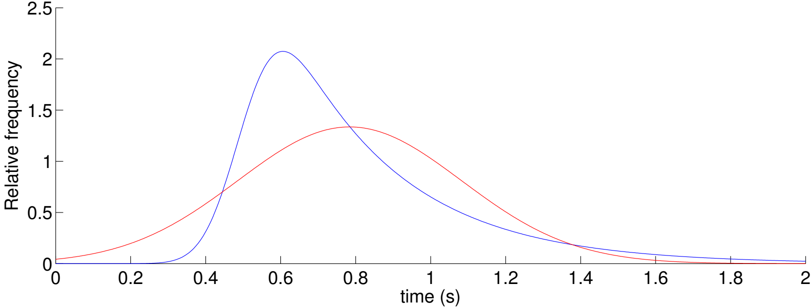

Stimulus
Response
RT, accuracy

Response times (RT)

- Response times (RT) are a popular technique for studying cognitive processes.
- Mean response times can tell us whether one process is faster than another
- However, *only* using mean RT can mask important details, that we could learn by looking at the distributions of RT

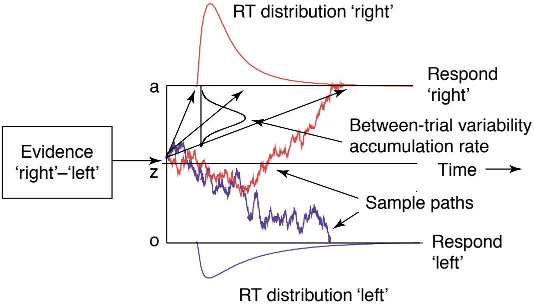
RT MODELS

- Considering only mean RT can mask important details
- By looking at the whole distribution, we can observe in more detail differences across conditions, such as how fast and slow responses change

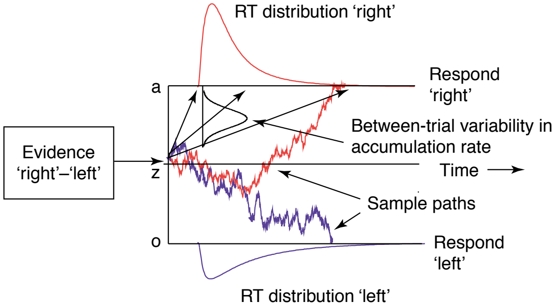


RT MODELS - WIENER DIFFUSION MODEL

- The Wiener diffusion model is a process model to explain reaction times
- It is based on the notion that evidence is accumulated in a noisy way (a random walk) until a bound is reached, at which point a decision is made

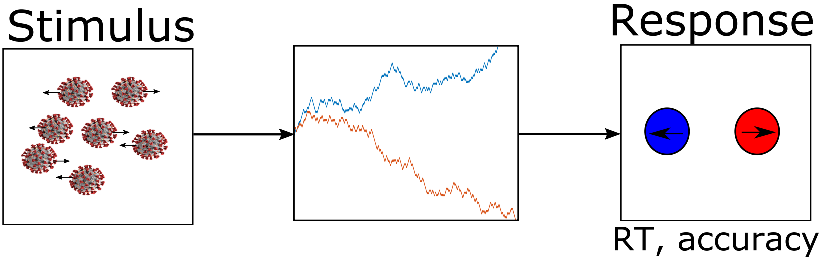


ACCUMULATOR MODELS

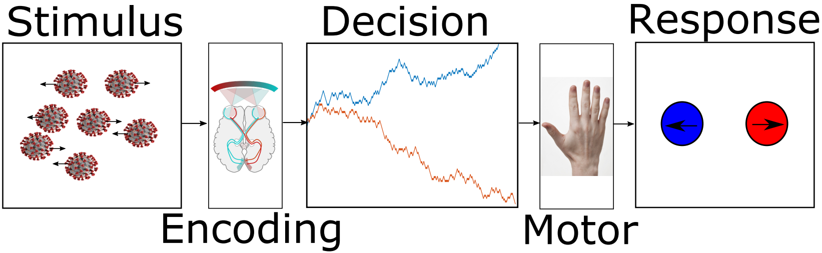


- The parameters of these models then can then be interpreted in a psychologically meaningful way, e.g.
  - "drift rate" - indicates the speed at which information accumulates, quantifying perceptual sensitivity
  - "threshold" -indicates the conservatism of the subjects in making a decision

MODEL



MODEL



Limitations of RT analysis

A model-based approach to RTs can provide us more insight than just using mean RTs. However, there are three significant drawbacks with using RTs to study the temporal dynamics of cognitive processes:

- The RT measures the end of the process, so the temporal dynamics are necessarily inferred
- If the decision is a multi-stage process, it is not possible to segment the reaction times into the contributions from the two or more processes
- There may be a mix of two (or more) different classes of trials. A single trial cannot be classified as belonging to one type or the other using only the RT.

Arm movements

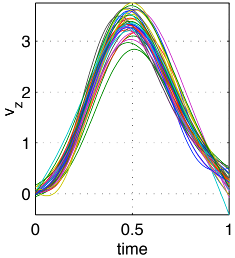
- Arm movements are the “work-horse” of the field of motor control
- This is because arm movements are easy to work with, but still face many issues involved in planning and executing movement (e.g. dealing with redundancy)
- Much of our knowledge about planning and executing movements comes from arm movement studies

Arm movements

- Arm pointing movements are useful because:
  - They are natural responses
  - They can be initiated quickly
  - They take long enough that you can change your mind during the movement

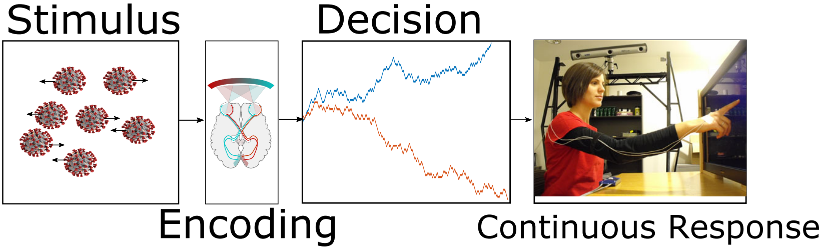
Features of arm movements

- Point-to-point arm movements have been studied extensively in the motor control literature
- These movements are highly stereotypical

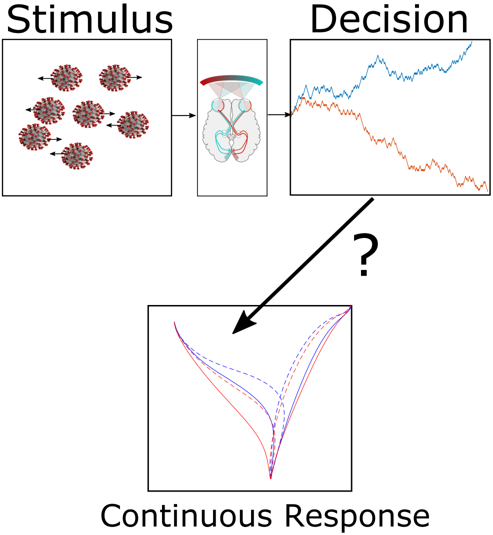


- We can use this property of trajectories to see when there are multiple processes occurring
- When the trajectory does not look like the stereotypical one, we deduce that something else is occurring rather than a single decision

MODEL



Model



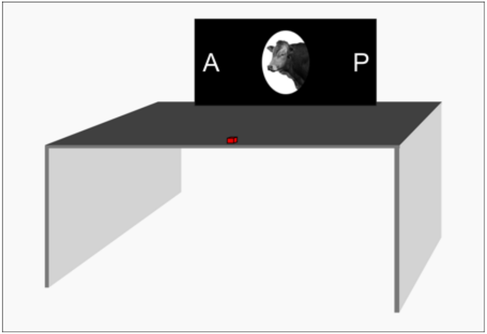
Masked congruence priming

Finkbeiner & Friedman (2011), PLoS ONE

- In this task, subjects had to decide whether the stimulus was a person or an animal.

Masked congruence priming

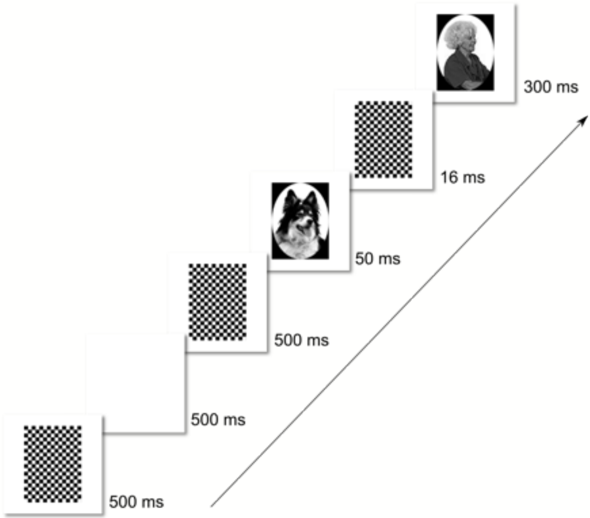
Finkbeiner & Friedman (2011), PLoS ONE



- Subjects pointed to a target corresponding to the stimulus (A for animal, P for person)

Masked congruence priming

Finkbeiner & Friedman (2011), PLoS ONE



Masked congruence priming

Finkbeiner & Friedman (2011), PLoS ONE

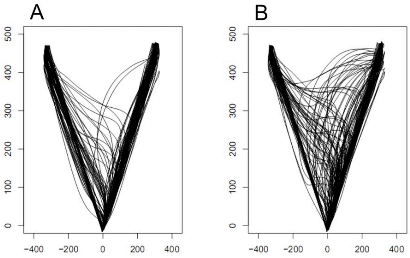
- There were two types of primes:
  - Novel primes - the primes was never a target
  - Repeated primes - the prime was also a target

Masked congruence priming

- In these tasks, although the primes are not consciously observed, they affect behaviour.
- They will facilitate the movement if the prime is congruent, and cause subjects to move the wrong way initially sometimes when incongruent
- This study asked whether repeated primes (which could have a prepared stimulus-response action prepared) are different from novel primes, which are never consciously seen so may not have this representation

MASKED CONGRUENCE PRIMING

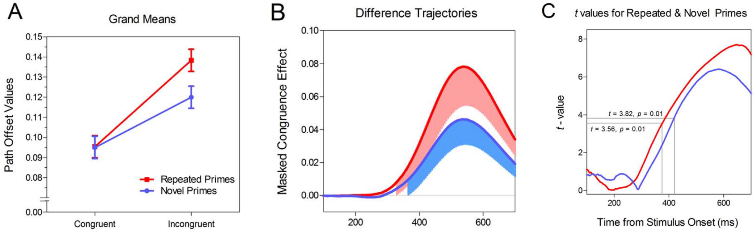
FINKBEINER & FRIEDMAN (2011), PLOS ONE



- Subjects were required to begin moving before 350 ms.
- In the congruent conditions (A), most of the movements were straight to the correct target
- In the incongruent condition (B), the subjects more often move initially in the wrong direction.

Masked congruence priming

Finkbeiner & Friedman (2011), PLoS ONE

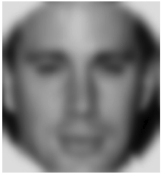


- By looking at the path offset (distance from a straight line path), we can observe differences between the two types of primes
- Specifically, the repeated primes caused the trajectories to deviate more than the novel primes
- Additionally, we can observe that the repeated primes have an earlier effect than the novel primes

POINTING TO HYBRID FACES

- We can apply a spatial filter to images to extract the low spatial frequency component, and the high spatial frequency component
- It is believed that these two components are processed differently

HSF Face



LSF Face

Pointing to hybrid faces

Awasthi, Friedman & Williams (2011), Neuropsychologia

LSF **F**emale- HSF **F**emale (**FF**)

LSF **M**ale- HSF **M**ale (**MM**)

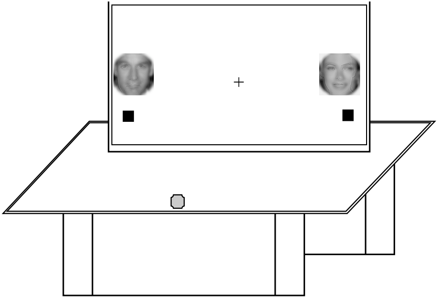
LSF **M**ale- HSF **F**emale (**MF**)

LSF **F**emale- HSF **M**ale (**FM**)

- In this task, subjects had to decide whether a hybrid face, consisting of a superimposed high spatial frequency (HSF) and low spatial frequency face (LSF) was male or female
- The HSF face was salient

Pointing to hybrid faces

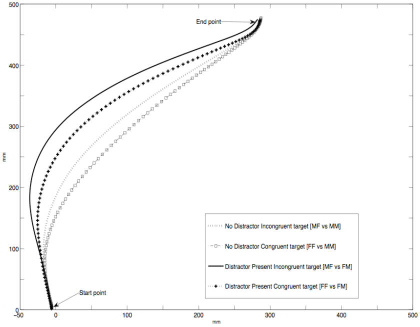
Awasthi, Friedman & Williams (2011), Neuropsychologia



- Subjects had to point to the either the male or female face (counterbalanced across subjects)
- Subjects were forced to begin moving within 350 ms, but had plenty of time to complete the movement
- We recorded the movement of the fingertip using a motion capture system

Pointing to hybrid faces

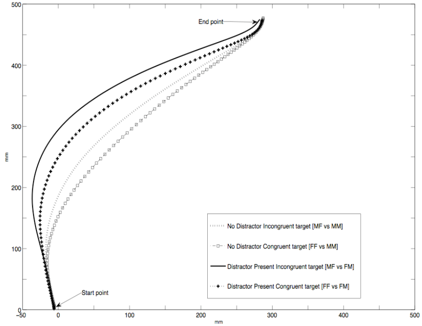
Awasthi, Friedman & Williams (2011), Neuropsychologia



- For incongruent targets (e.g. female LSF superimposed on a male HSF), trajectories were more curved.
- When the LSF component of the wrong target was the same sex as the target, the trajectories were also curved.
- These effects were additive

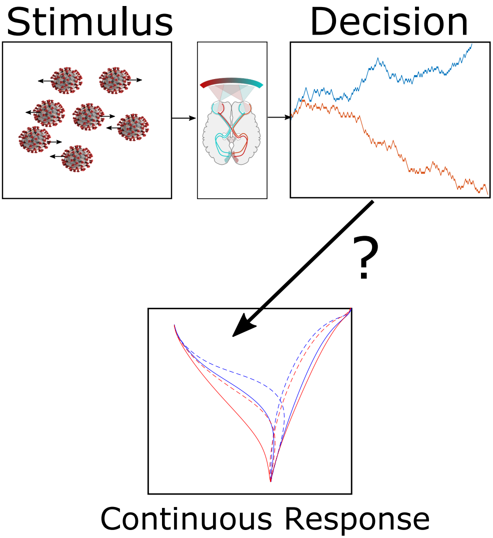
Pointing to hybrid faces

Awasthi, Friedman & Williams (2011), Neuropsychologia



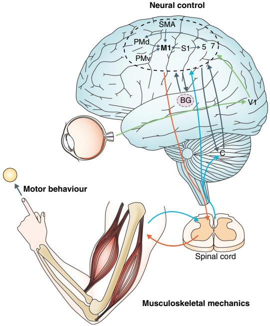
- Although the HSF face was more salient, subjects initially reached towards the LSF face.
- We can conclude from this that the LSF components are likely processed earlier than HSF for this task.

MODEL



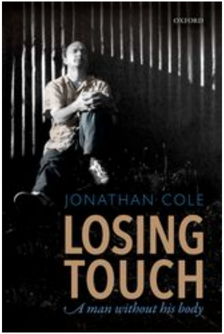
Muscles and the brain

- 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?

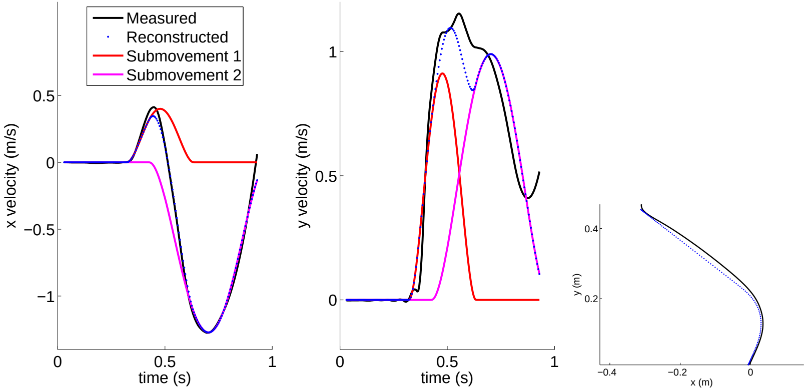
Intermittent control

- 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

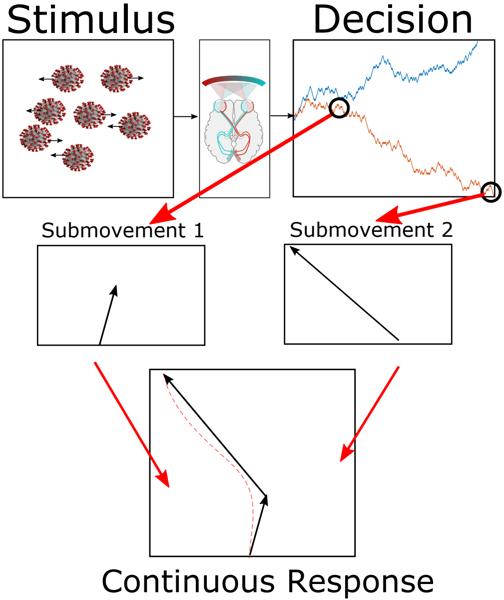
- We assume that the observed arm movements are made up of *submovements* - discrete, stereotypical movements that are serially concatenated and overlapping in time
- Submovements are assumed to be straight.
- The resultant movement may be curved due to the superposition of multiple submovements (starting at different times)
- They are *discrete* rather than continuous at the planning stage, and planned in a feed-forward manner.
- 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



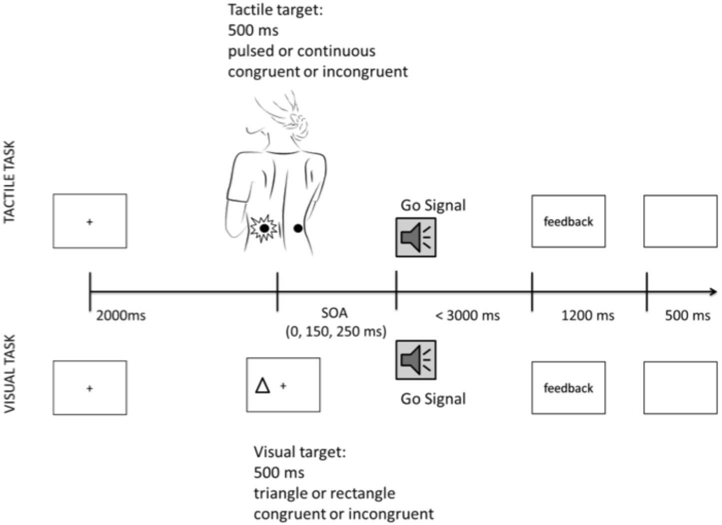
- This method gives the onset times T_0 and amplitudes D_x,D_y of the submovements, which are a compact description of *intent* at a specific time.

Model


Stimulus
Decision
Submovement 1
Submovement 2
Continuous Response

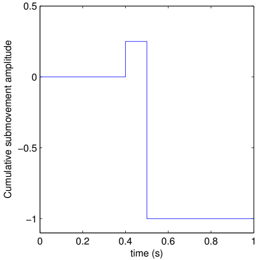
Tactile Simon task

Salzer & Friedman, in press

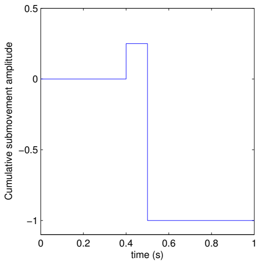


Cumulative submovement amplitude

- 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



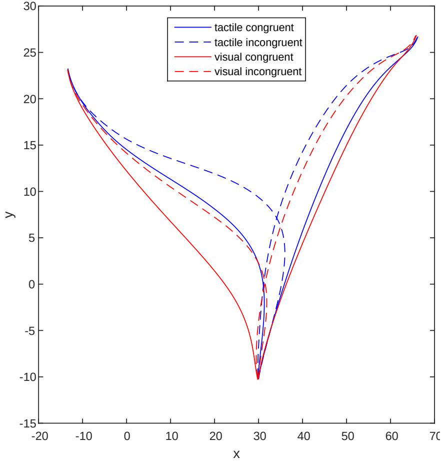
CUMULATIVE SUBMOVEMENT AMPLITUDE



- 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

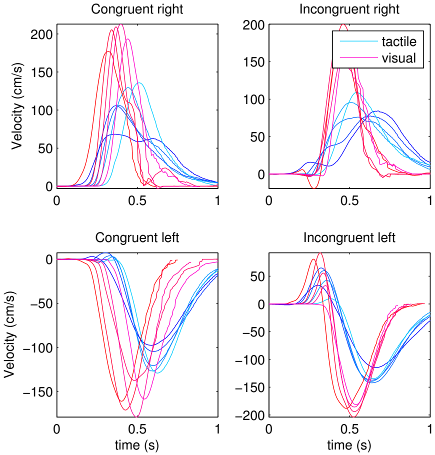
RESULTS - TRAJECTORIES

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

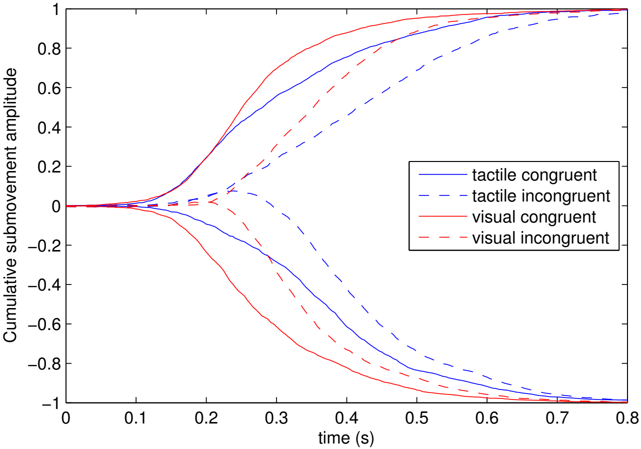


RESULTS

Incongruent movements do not just show inhibition but activation of the “wrong” target



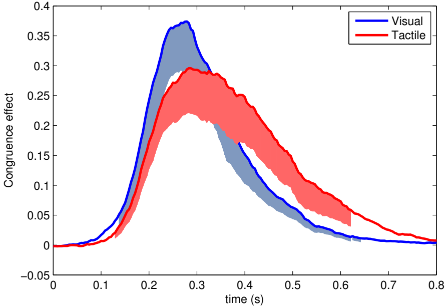
Results - cumulative submovement amplitude



- Cumulative submovement amplitude shows the temporal dynamics of the decision process
- Visual decisions start and resolve earlier

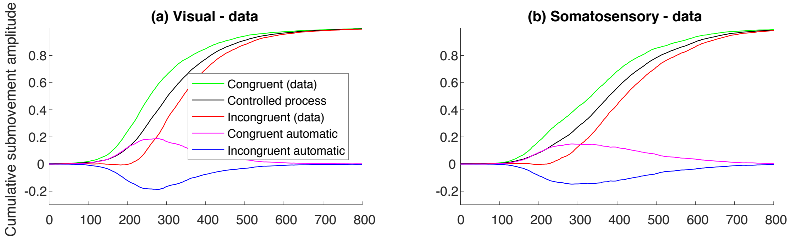
RESULTS - CONGRUENCE EFFECTS

- The interference effect of both stimuli start at a similar time
- While the duration of the interference is similar for the two modalities, the tactile stimuli shows a much slower decay



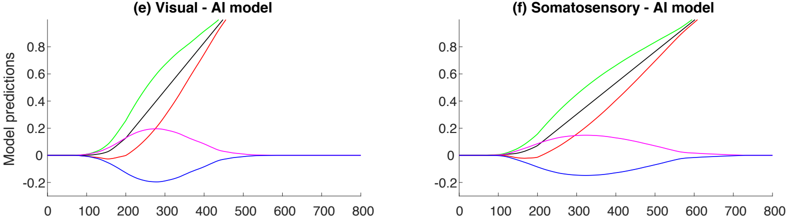
[Congruence effect = incongruent - congruent (cumulative submovement amplitude)]

Results - decomposition of CSA



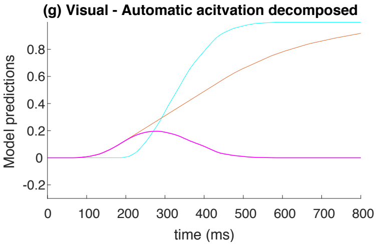
- We assume that
  - congruent = controlled + automatic
  - incongruent = controlled - automatic
- Then:
  - controlled = (congruent + incongruent) / 2
  - automatic = (congruent - incongruent) / 2

RESULTS - DECOMPOSITION OF CSA



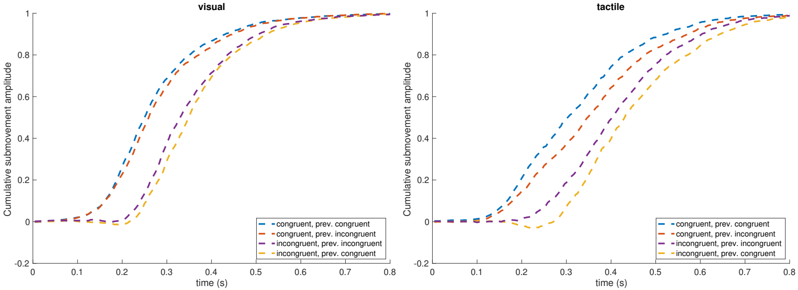
- We can also test whether selective suppression of activation is a good account (e.g. Ridderinkof 2002)

RESULTS - DECOMPOSITION OF CSA



- In this model, we assume there is an automatic activation, followed by delayed inhibition of this same process
- The main difference between visual and somatosensory Simon tasks is the much longer inhibition duration
- This technique gives us a way to look at the very early stages of the decision making process

Results - Effect of previous trial

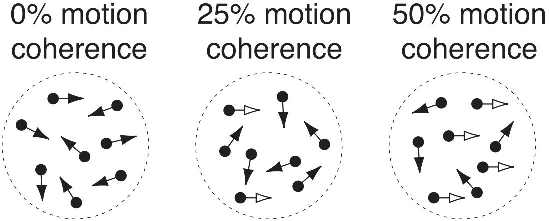


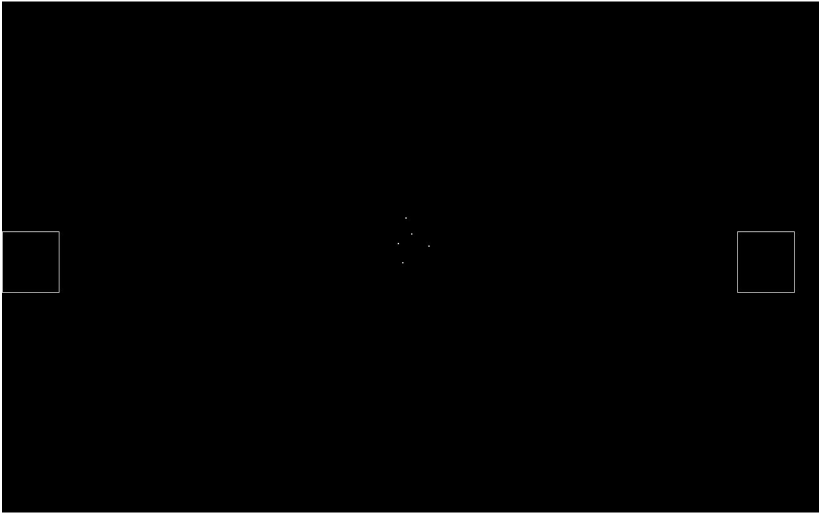
- We can also examine the effect of the previous trial on the congruence effect
- When the previous trial was congruent, there is a stronger congruence effect

Model-based analysis using arm movements

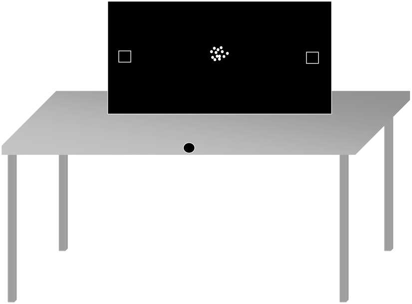
Friedman et al., 2013

- Subjects were required to point with the index finger to a target on a touch-screen in the direction of motion of a set of dots (random dot kinetogram), with variable coherence (3%, 6%, 12%, 24%, 48%)





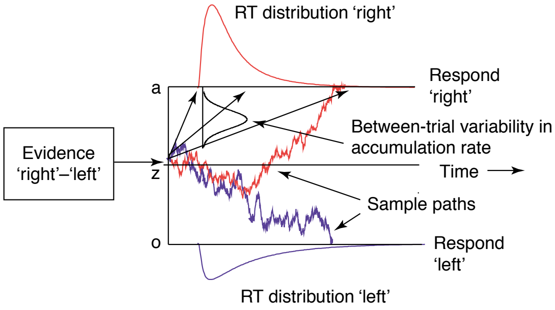
Experimental setup



- The stimuli was shown for 300 ms
- The subjects were required to begin moving within 350 ms of stimulus onset (i.e. before they had made a final decision)
- The trajectory of the fingertip was recorded with an Optotrak motion capture system at 200 Hz.

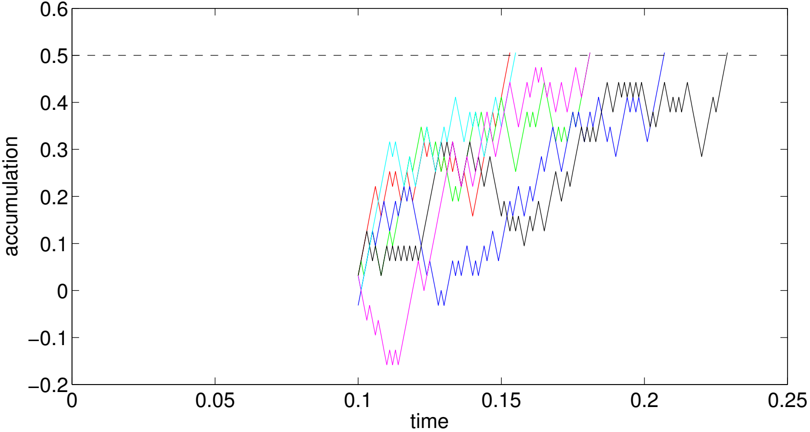
Accumulator model analysis

- We assume that there are two accumulator processes governing the movement
- The first is the decision process, which we model using a Wiener diffusion process
- Whichever bound is reached is the final decision



Accumulator model analysis

- The second process is the "movement initiation" process
- This ensures that the subjects start before 350 ms
- We model this as a one sided accumulator (when it hits the bound, make a movement)



Accumulator model analysis

- We have a competition between the decision process and the movement initiation process
- If the decision process finishes before the movement initiation process, the subject will make a single submovement directly to the target

Accumulator model analysis

- The likelihood of this is given by:

$$L = P(x_1 = a_1, T = t_0; z_1, v_1, a_1, T_{er1}, s) \\ \times (1 - P(x_2 = a_2, T \leq t_0; v_2, a_2, T_{er2}, s))$$

x=amount of accumulation, a = bound, t_0=onset of first submovement, v = drift rate, z_1 = starting point of diffusion process (bias), T_{er} = non-decision time, s = standard deviation

- $P(x_1 = a_1, T = t_0)$ is the PDF of the Wiener first passage time
- $P(x_2 = a_2, T < t_0)$ is the CDF of the Wald distribution

Accumulator model analysis

- If the movement initiation process finishes first, then make a submovement part of the way to the target
- When the first submovement is approximately half finished, make another submovement
- If in the meantime, the decision process has reached a bound, make the second submovement directly to the target.

Accumulator model analysis

- The angle to use is linearly related to the amount of evidence accumulated
- The likelihood of this is given by:

$$
\begin{aligned}
L =& P_{nt}(x_1 = \frac{\theta_1 - \theta_l}{\theta_r - \theta_l}, T = t_0; z_1, v_1, a_1, T_{er1}, s) \\
& \times P(x_2 = a_2, T = t_0; v_2, a_2, T_{er2}, s)) \\
& \times P(x_1 = 0, t_0 < T < t_1; z_1, v_1, a_1, T_{er1}, s)
\end{aligned}
$$

x=amount of accumulation, a = bound, t_0=onset of first submovement, t_1=onset of second submovement, v = drift rate, z_1 = starting point of diffusion process (bias), T_{er} = non-decision time, s = standard deviation

- $P_{nt}(x, t)$ is the PDF of the non-terminated Wiener process

Accumulator model analysis

- We then use maximum likelihood estimation to find the parameters

$$\ln\mathcal{L}(T_{er1}, a_1, V_{11}, \ldots, v_{15}, z_1, T_{er2}, a_2, v_2 | x_1, \ldots, x_n)$$
$$= \sum_{i=1}^{N} \ln f(x_i | T_{er1}, a_1, V_{11}, \ldots, v_{15}, z_1, T_{er2}, a_2, v_2 | x_1, \ldots, x_n)$$

- For the decision process, we assume that only the drift rate varies across conditions (coherence levels)
- For the movement initiation process, we assume the same parameters for all conditions
- We use simplex (fminsearch in matlab), followed by simulated annealing to find the best model parameters

Accumulator model analysis

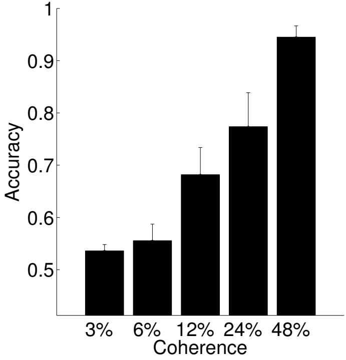
- To check the fit, we use the parameters to generate movements
- We fit the model only using submovement onset time (t_0) and angle, so we can simulate the accumulators to find these values
- However, for the rest of the values we need to make some assumptions

A model of movement production

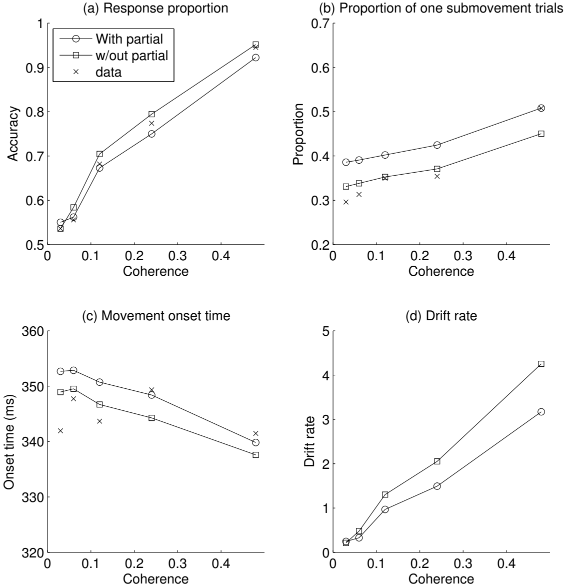
- We defined a simple model for movement production, based on some assumptions (we fit the values from the data for each subject):
  - For one submovement trials, the onset time and amplitude are determined.
  - The duration of one submovement movements was assumed to be normally distributed
  - For two submovement trials, the amplitude was assumed to be normally distributed
  - The second submovement duration was assumed to be a linear function of the amplitude
  - The second submovement was assumed to start a certain proportion of the way through the first submovement

Accuracy

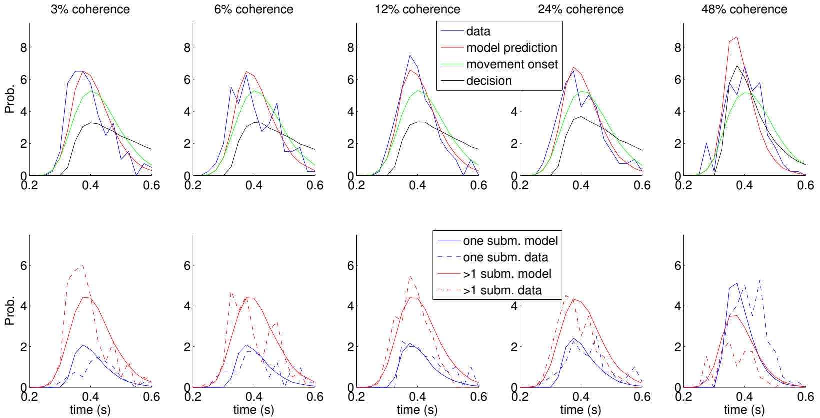
- The accuracy data shows an increase of accuracy with coherence, as expected. 2 subjects which did not show this increase were not included in further analysis.



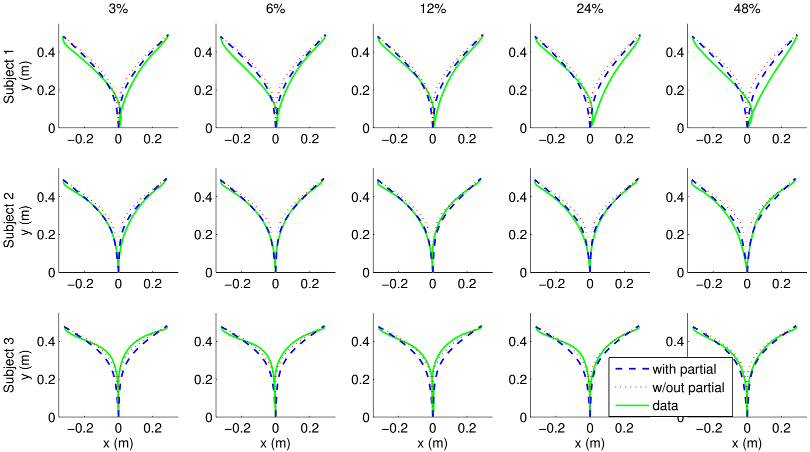
Model predictions



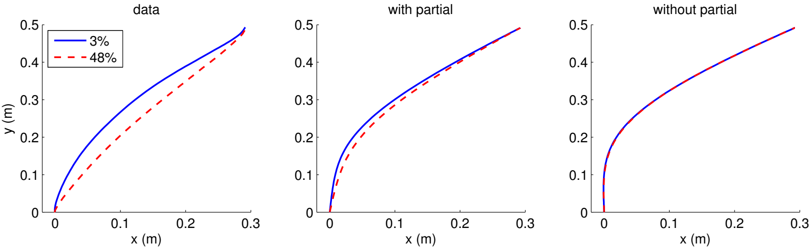
Onset times


3% coherence
6% coherence
12% coherence
24% coherence
48% coherence
data
model prediction
movement onset
decision
one subm. model
one subm. data
>1 subm. model
>1 subm. data
Prob.
time (s)

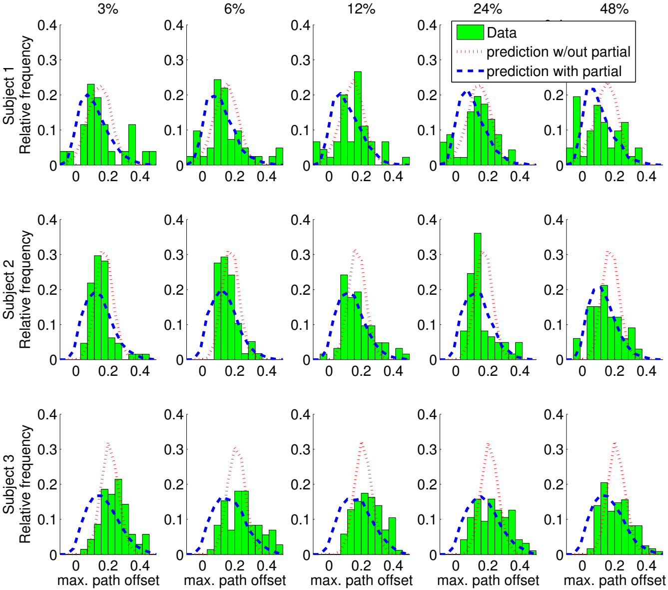
Trajectories



Trajectories



Path offset


3%
6%
12%
24%
48%
Data
prediction w/out partial
prediction with partial
Subject 1
Subject 2
Subject 3
Relative frequency
max. path offset

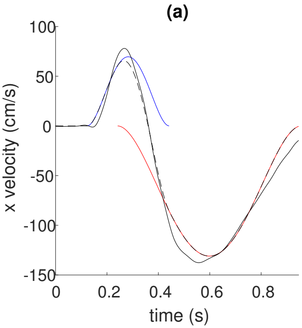
RESULTS

- Using accumulator models combined with submovements, we can predict reasonably well arm movements made during perceptual decision making
- We can use this technique to probe further when and why submovements are generated
- The technique can also be used to provide further constraints for models of perceptual decision making

Decision making informing motor control

- As well as using arm movements to inform us about decision making, we can also learn about how and when we produce of arm movements using decision making experiments

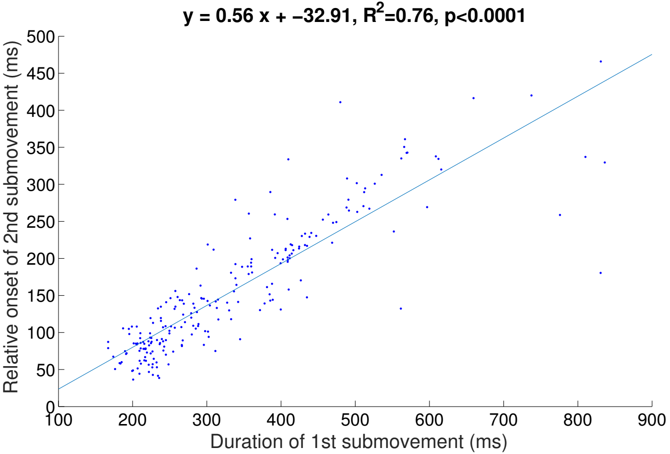
Submovement initiation



- Continuous movements can be decomposed into a number of temporally overlapping submovements
- When we make multiple submovements, when should we produce the “next” submovements?

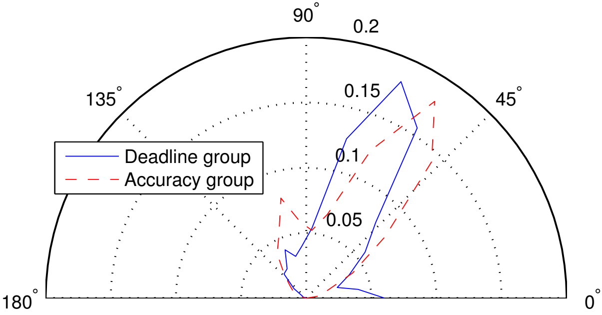
Submovement initiation

- Some possible options:
  - As soon as possible (200 ms)
  - As soon as enough information is available
  - Fixed proportion of the submovement duration



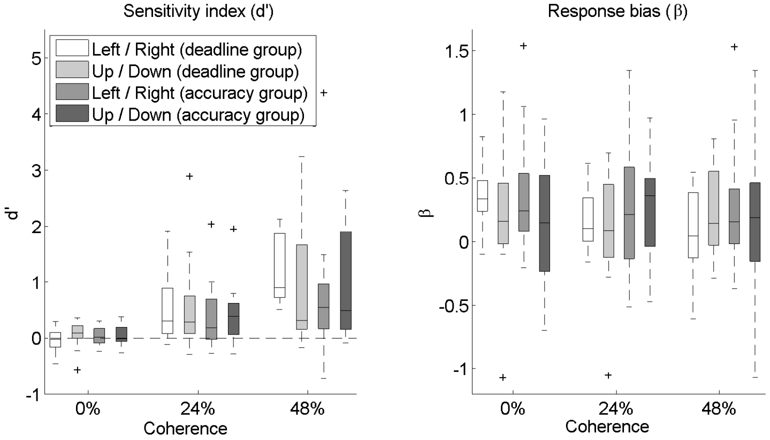
- For nearly all the subjects, the second submovement is produced at a fixed proportion of submovement duration (around half)

Movement bias



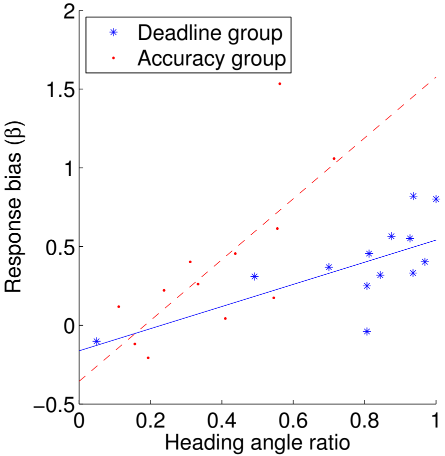
- In the reaching experiments described before, subjects typically show a bias for movements towards the right

Decision bias



- In a random dot kinematogram experiment, we observe a *response bias* towards the right (on average)
- Are the two related?

Movement and decision bias



- We find a significant correlation between initial motor bias and the response bias

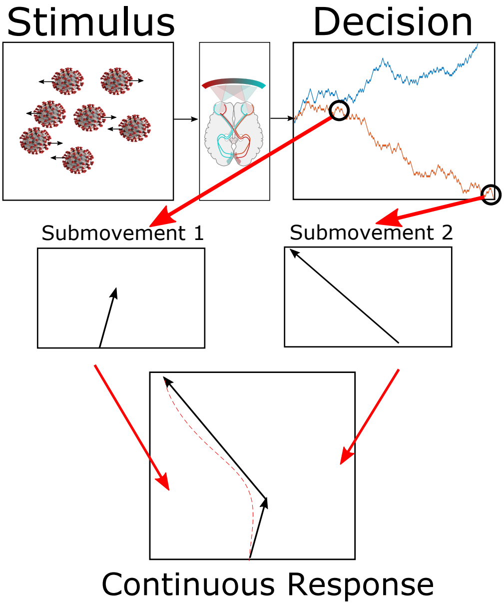
Movement and decision bias

- While the subjects had sufficient time to change their mind, the initial motor bias dictated the response bias
- Motor biases and decision biases appear to be part of the same decision process
- Motor biases should be taken into account in response selection, e.g. when designing voting machines

Conclusions

- Using arm movements (rather than RTs) to record responses can provide significantly more details about cognitive processing
- In particular, they are good for situations with multiple processes are going on
- We have shown that additionally, arm movements can be exploited to reveal the current state of the decision process at times before the final decision is made, on a trial-to-trial basis only binary decisions.
- By using detailed modeling, we can also access information about the timing of different processes

MODEL


Stimulus
Decision
Submovement 1
Submovement 2
Continuous Response

CONCLUSIONS

- All movements involve decision making:
  - When to start moving
  - How far to move
  - How fast to move
  - Which path to take
- To fully understand and model the processes of motor control, it is necessary to take into account decision making process
- Likewise, using decision making paradigms can inform us of how motor control takes place

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