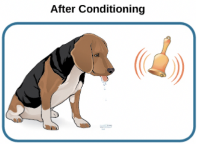
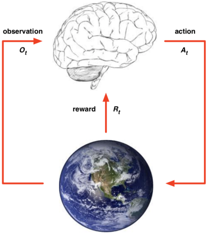
Neuromechanics of Human Motion

Human Behaviour

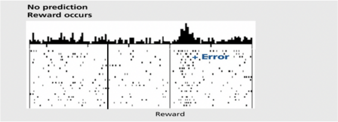
Joshua Cashaback, PhD

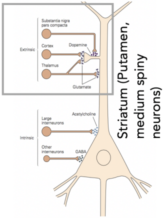
Recap — Reinforcement Learning



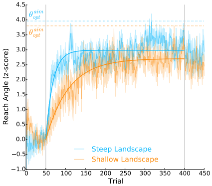


Recap — Reinforcement Learning





Shift unknown to participants



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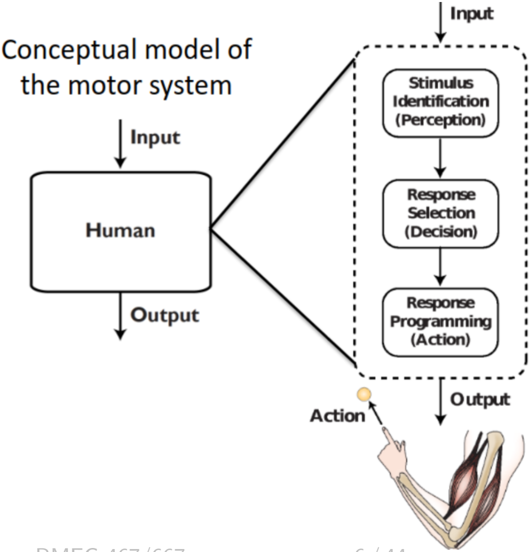
Lecture Objectives — Human Behaviour

Brief Overview of Stereotypical Features of Human Behaviour

1. Reaction Time
   - Hick's Law
2. Movement Time
   - Speed-Accuracy Tradeoff
   - Fitt's Law
3. Velocity Profiles
   - Bell-shaped
4. Signal Dependent Noise
5. Behaviour of Redundant Systems
   - Joint Space, Muscle Space, Load Sharing

Reaction Time — Hick's Law

Reaction Time — Premotor and Motor



Reaction Time

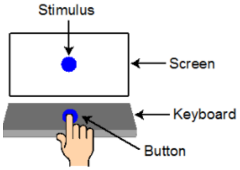
Reaction Time

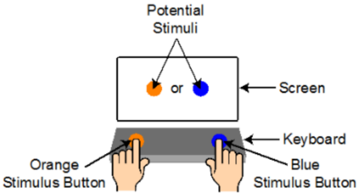
Interval between stimulus presentation and initiation of motor response

Factors that influence reaction time

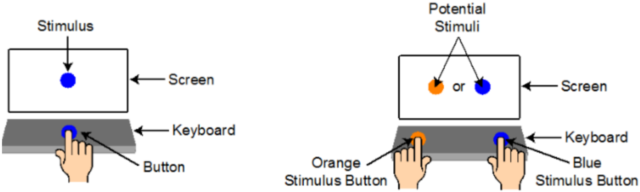
1. The number of response choices (Hick's Law)
2. Stimulus modality & intensity
3. Stimulus-response compatibility
4. Anticipation

Reaction Time — Number of Choices





Reaction Time — Number of Choices



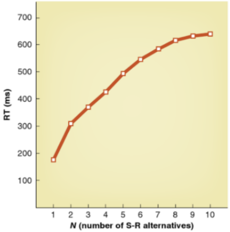


FIGURE 2.6 The relationship between the number of possible stimulus–response (S-R) alternatives and reaction time.

Reprinted by permission from Schmidt and Lee 2011; Data from Merkel 1885.

Reaction Time — Number of Choices

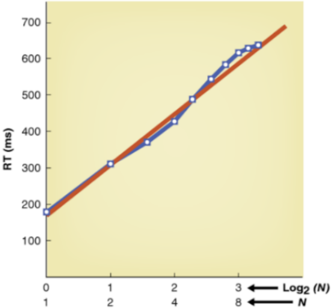


FIGURE 2.7 Hick's Law: The relation between choice RT and number of S-R alternatives (*N*) is replotted using Merkel's data from figure 2.6, with choice RT as a function of $\text{Log}_2(N)$.

Reprinted by permission from Schmidt and Lee 2011; Data from Merkel 1885.

Reaction Time — Number of Choices

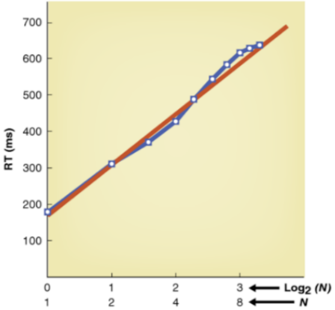


FIGURE 2.7 Hick's Law: The relation between choice RT and number of S-R alternatives (*N*) is replotted using Merkel's data from figure 2.6, with choice RT as a function of $Log_2(N)$.

Reprinted by permission from Schmidt and Lee 2011; Data from Merkel 1885.

$$RT = a + b \cdot log_2(N)$$

Reaction Time — Hick's Law

Hick's Law (1951)

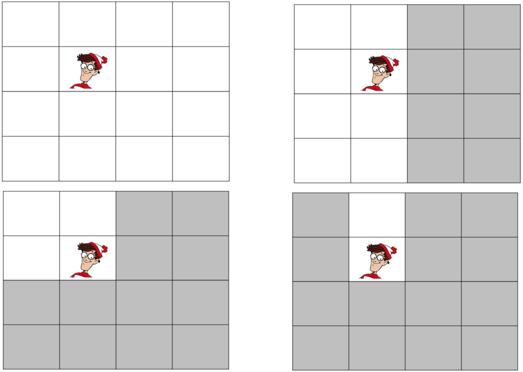
$$RT = a + b \cdot log_2(N)$$

1. RT: Reaction Time
2. a: y-intercept (time for single choice)
3. b: slope (task, individual differences, age)
4. $log_2(N)$: 'bits' of information
5. N: number of choices

Reaction Time — Hick's Law

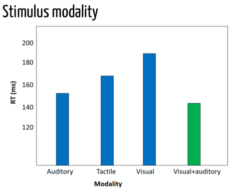
Why $log_2(N)$?

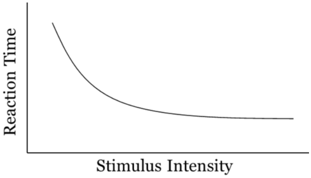
Binary Search (splitting the search in halves)



$log_2(16) = 4$ **OR** $2*2*2*2 = 16$ (i.e., 4 binary decisions)

Reaction Time — Stimulus modality & intensity





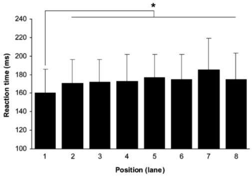


FIGURE 2—2004 Olympic Games RT. RT from the 100-m sprint and 110/100-m hurdles events grouped according to starting position. Data are expressed as mean and standard deviation (*$P < 0.01$, one-way ANOVA).

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Reaction Time — Stimulus-response compatibility

Example A: Spatially Compatible

Example B: Spatially Incompatible

Less compatible = greater reaction time

Reaction Time — Anticipation

Spatial Anticipation

Temporal Anticipation

Spatial-Temporal Anticipation

Anticipating can decrease reaction time, but can come at a cost (e.g., false starts)

Movement Time — Fitt's Law

Speed-Accuracy Tradeoff

Movements can be made quickly at the cost of accuracy, or accurately at the cost of speed.

Speed-Accuracy Tradeoff — Fitt's Law

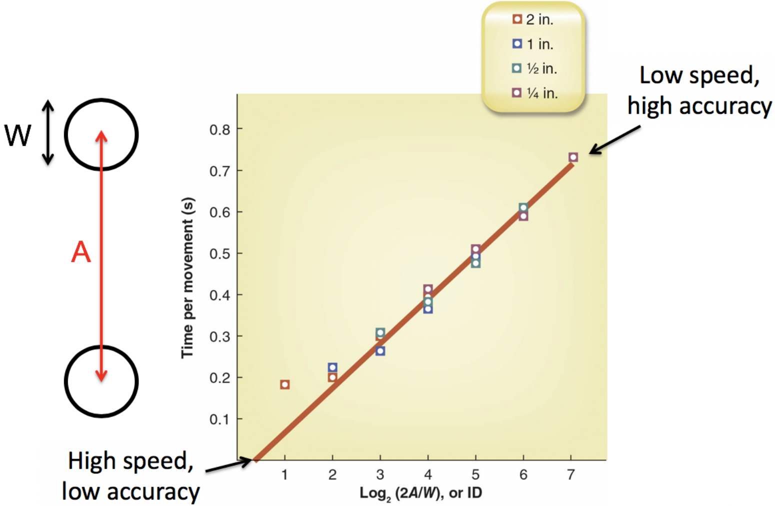
Fitts (1954) discovered the relation between movement amplitude, accuracy, and movement time

$$MT = a + b\left[log_2\left(\frac{2A}{W}\right)\right]$$

1. MT: Movement Time
2. a: y-intercept (fastest possible movement time)
3. b: slope (task, individual differences, age)
4. $log_2(\frac{2A}{W})$: index of task difficulty
5. A: distance of reach
6. W: width of target

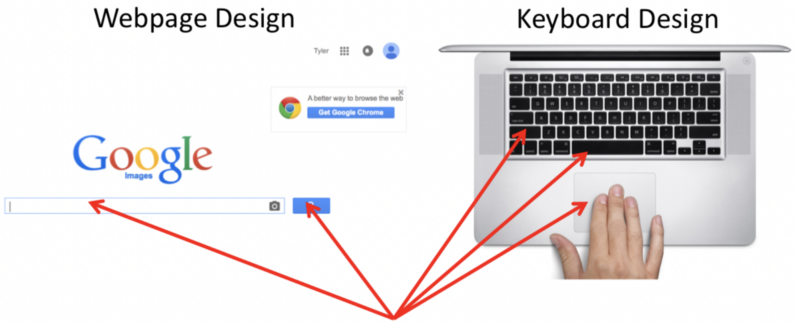
Short reach and wide targets are less difficult

Speed-Accuracy Tradeoff



Reprinted by permission from Schmidt and Lee 2011; Data from Fitts 1954.

Speed-Accuracy Tradeoff

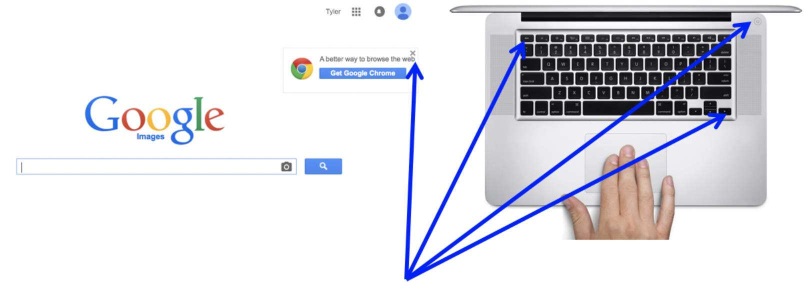


Frequently used areas (keys) are **larger** to **reduce accuracy demand** and **save time**

Speed-Accuracy Tradeoff

Webpage Design

Keyboard Design



Infrequently used areas (keys) are **smaller** to **increase accuracy demand** at the **expense of time cost.** This also **minimizes risk of error.**

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Speed-Accuracy Tradeoff

Why is there a speed-accuracy tradeoff?

Speed-Accuracy Tradeoff

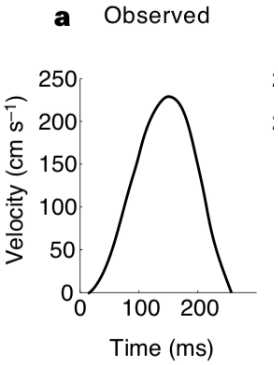
Why is there a speed-accuracy tradeoff?

Likely candidates:

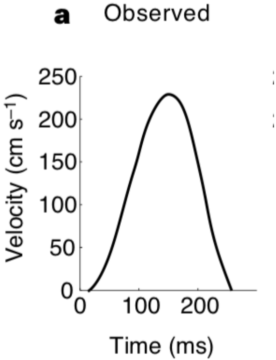
1. signal-dependent noise
2. time delays

Bell-Shaped Velocity Profiles

Bell-Shaped Velocity Profiles



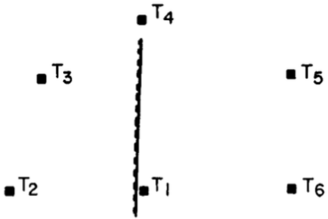
Bell-Shaped Velocity Profiles

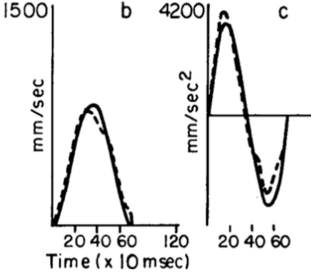


Why do these stereotypical velocity profile shapes arise from?

Bell-Shaped Velocity — Min(Jerk)

Is the Brain optimizing Kinematics?





Flash and Hogan (1985) — Minimum Jerk Trajectories

Journal of Neuroscience, 5(7), 1688-1703

Bell-Shaped Velocity — Min(Jerk)

Flash and Hogan (1985) — Minimum Jerk Trajectories

T = movement time; t = current time

x_i, y_i = initial x,y position; x_f, y_f = final x,y position

$x(t)$, $y(t)$ = current x,y position

$$x(t) = x_i + (x_f - x_i)\left[10(t^3/T^3) - 15(t^4/T^4) + 6(t^5/T^5)\right]$$

$$y(t) = y_i + (y_f - y_i)\left[10(t^3/T^3) - 15(t^4/T^4) + 6(t^5/T^5)\right]$$

$$\dot{x}(t) = (x_f - x_i)\left[30(t^2/T^3) - 60(t^3/T^4) + 30(t^4/T^5)\right]$$

$$\dot{y}(t) = (y_f - y_i)\left[30(t^2/T^3) - 60(t^3/T^4) + 30(t^4/T^5)\right]$$

$$\ddot{x}(t) = (x_f - x_i)\left[60(t^1/T^3) - 180(t^2/T^4) + 120(t^3/T^5)\right]$$

$$\ddot{y}(t) = (y_f - y_i)\left[60(t^1/T^3) - 180(t^2/T^4) + 120(t^3/T^5)\right]$$

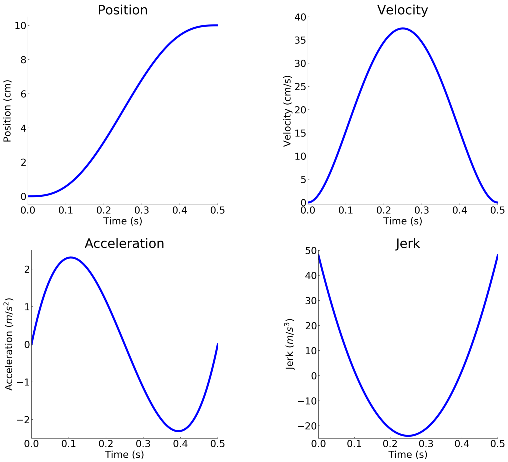
$$\dddot{x}(t) = (x_f - x_i)\left[60(t^0/T^3) - 360(t^1/T^4) + 360(t^2/T^5)\right]$$

$$\dddot{y}(t) = (y_f - y_i)\left[60(t^0/T^3) - 360(t^1/T^4) + 360(t^2/T^5)\right]$$

Bell-Shaped Velocity — Min(Jerk)

Flash and Hogan (1985) — Minimum Jerk Trajectories

$T = 0.5$; x_i, $y_i = 0$, 0; x_f, $y_f = 0$, 10



Bell-Shaped Velocity — Min(Joint-Moment Rate)

Is the Brain optimizing Dynamics?

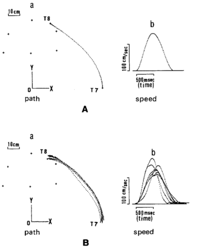


Fig. 4A and B. Large free movements between two targets ($T7 \rightarrow T8$); the starting posture is stretching an arm in the side direction and the end point is approximately in front of the body. **A** Hand trajectory predicted by the minimum torque-change model. **a** shows the path and **b** shows the corresponding speed profile. **B** Observed hand trajectories for the seven subjects. **a** shows the paths and **b** shows the corresponding speed profiles

Uno et al (1989) Biol. Cybern. 61, 1688-1703

Signal Dependent Noise

Signal Dependent Noise

$$sdn = \sigma \cdot u$$

1. signal dependent noise (*sdn*) scales with the control signal (u) by some factor (σ)
2. increase in variance with a greater control input
3. multiplicative noise

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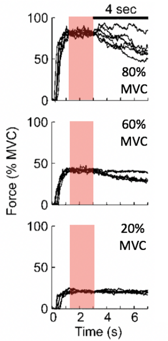
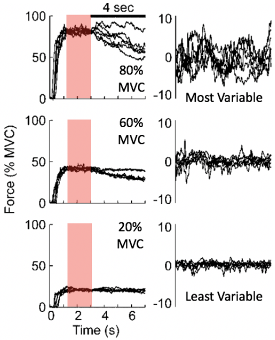
Signal Dependent Noise — Motor Force Variability



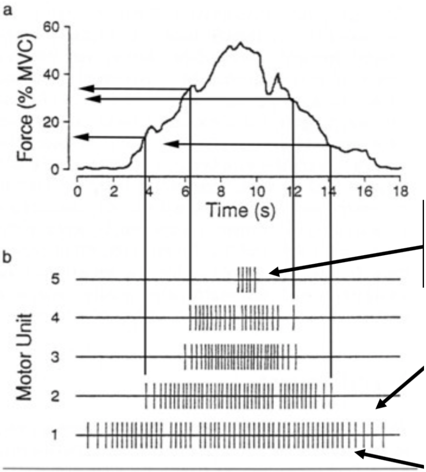
Jones, Hamilton, Wolpert (2002)

Signal Dependent Noise — Motor Force Variability



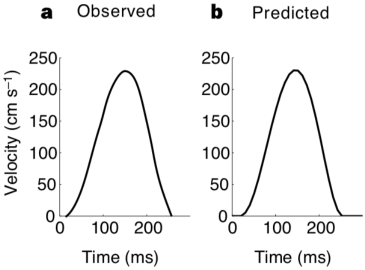
Jones, Hamilton, Wolpert (2002)

Signal Dependent Noise — Motor Units



Signal Dependent Noise — Min(sdn)

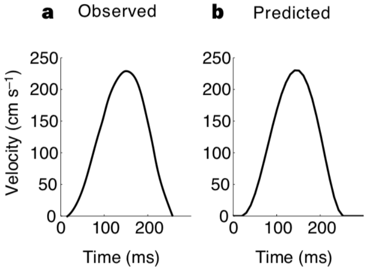
Is the Brain minimizing noise?

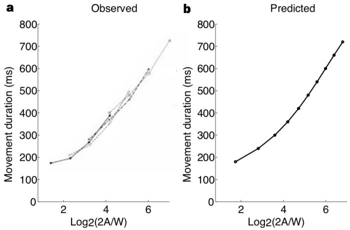


Harris and Wolpert (1998) — Nature, 394, 780-784

Signal Dependent Noise — Min(sdn)

Is the Brain minimizing noise?



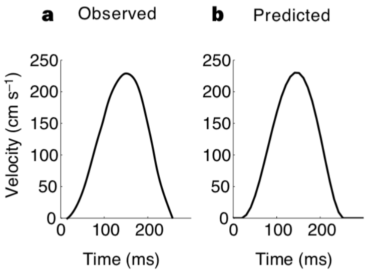


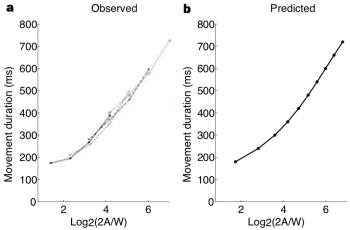
Harris and Wolpert (1998) — Nature, 394, 780-784

Predicts bell-shaped velocity and Fitt's Law!

Signal Dependent Noise — Min(sdn)

Is the Brain minimizing noise?





Harris and Wolpert (1998) — Nature, 394, 780-784

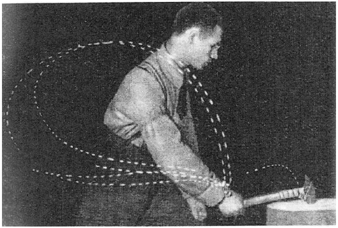
Predicts bell-shaped velocity and Fitt's Law!

But is all variability bad?

Behaviour of Redundant Systems

Redundant Systems — Joint Space

Bernstein (1922)



- cyclogram: a photograph made by taking intermittent exposures (light attached to the wrist in image above)
- Humans display lots of variability between successive movements, but can repeatedly accomplish a task goal (e.g., strike a chisel)

Redundant Systems — Joint Space

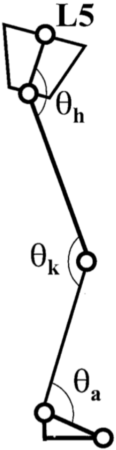
Uncontrolled manifold hypothesis

The nervous system does not intervene (uncontrolled) with movement variability along the task-irrelevant dimension (manifold)

Pistol shooting example (Scholz, Schöner, Latash, 2000):

1. Task-Irrelevant: No bearing on task success
   - Movement of the shoulder, elbow, and wrist *without* the location of your fingertip
2. Task-Relevant: Influences task success
   - Movement of the shoulder, elbow, and wrist *changes* the location of your fingertip
3. Steps: calculate average trajectory, Jacobian null space, & partition variability along the null space (task-irrelevant) and orthogonal (task-relevant) dimensions.

Redundant Systems — Joint Space



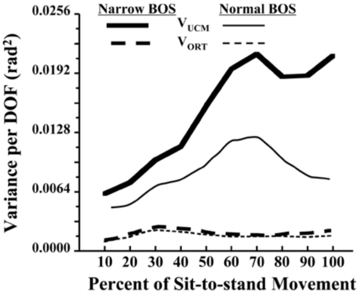


Figure 5—Variance of joint angles reflecting flexible patterns of joint coordination (V_{UCM}), consistent with a stable value of the horizontal path of the body's center of mass, and variance leading to fluctuations in the horizontal CM path (V_{ORT}) when standing up from either a narrow (thick solid line) or normal (thin solid line) base of support, computed at each percentage of normalized movement time. V_{ORT} for narrow base is represented by a thick dashed line, while that for the normal base is represented by a thin dashed line. Reproduced with permission from Scholz et al., 2001.

Redundant Systems — Load Sharing

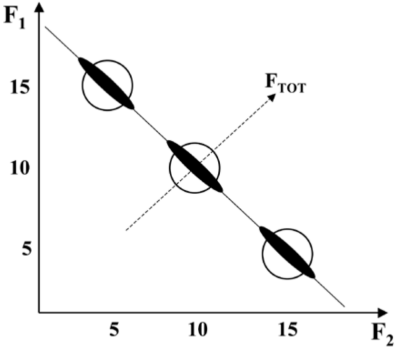


Figure 1—An illustration of the two basic features of synergies. A person tried to produce the same total force of 20 N with two fingers. Three sharing patterns are illustrated: 5:15 N, 10:10 N, and 15:5 N. This means that with changes of total force (F_{TOT}) both finger forces change in the same direction (i.e., positive co-variation along the dashed lines). Data distri-

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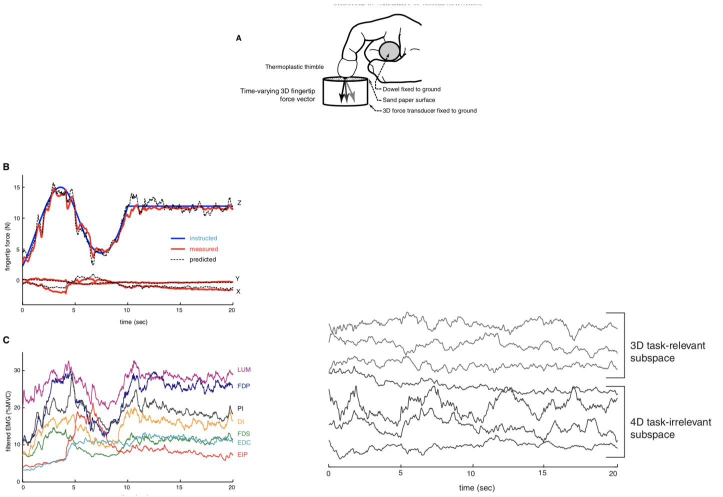
Redundant Systems — Muscle Space



3D Task-relevant (EMG variability related to 3D force vector)

4D Task-Irrelevant (7D EMG - 3D Force = 4D task irrelevant dimension)

Redundant Systems — Note on Dimensionality Reduction

We observe reduced dimensionality with PCA (a.k.a, 'synergies')

1. Interpretation 1: Nervous system stores and uses a particular set of motor commands (EMG) / movement pattern given a task
   - neural and biomechanical constraints may contribute
   - storage problems?
2. Interpretation 2: The observed motor commands / movement patterns fall out of the nervous system's control policy
   - solves storage problem
   - control policy can account for neural or biomechanics constraints
   - But we do learn and store motor memories
3. Interpretation 3: Answer between these two extremes?

Summary

How do computational models explain different Features of Human Behaviour?

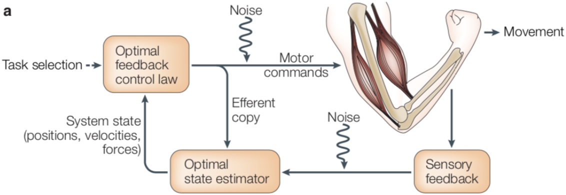
1. Reaction Time
   - Hick's Law
2. Movement Time
   - Speed-Accuracy Tradeoff
   - Fitt's Law
3. Velocity Profiles
   - Bell-shaped
4. Signal Dependent Noise
5. Behaviour of Redundant Systems
   - Joint Space, Muscle Space, Load Sharing

Questions???

Next Class

Optimal Feedback Control and Human Behaviour

1. Fitt's Law
2. Bell-shaped Velocity Profiles
3. Task-Relevant and Task-Irrelevant Variability



Homework

1. Play around with Hick's Law and Fitt's Law equations
2. Replicate the slide showing pos, vel, acc and jerk, using Flash and Hogan's equations
3. Use Inverse Kinematics to calculate angular position, velocity, and acceleration (**Grad Students**)
4. Use the equations of motion to calculate the required joint moments (Q) to produce these kinematics (**Grad Students**)
5. Run a forward simulation with the calculated joint moments (Q) as an input (Euler Integration) (**Grad Students**)

Acknowledgements

Michael Carter

Tyler Cluff