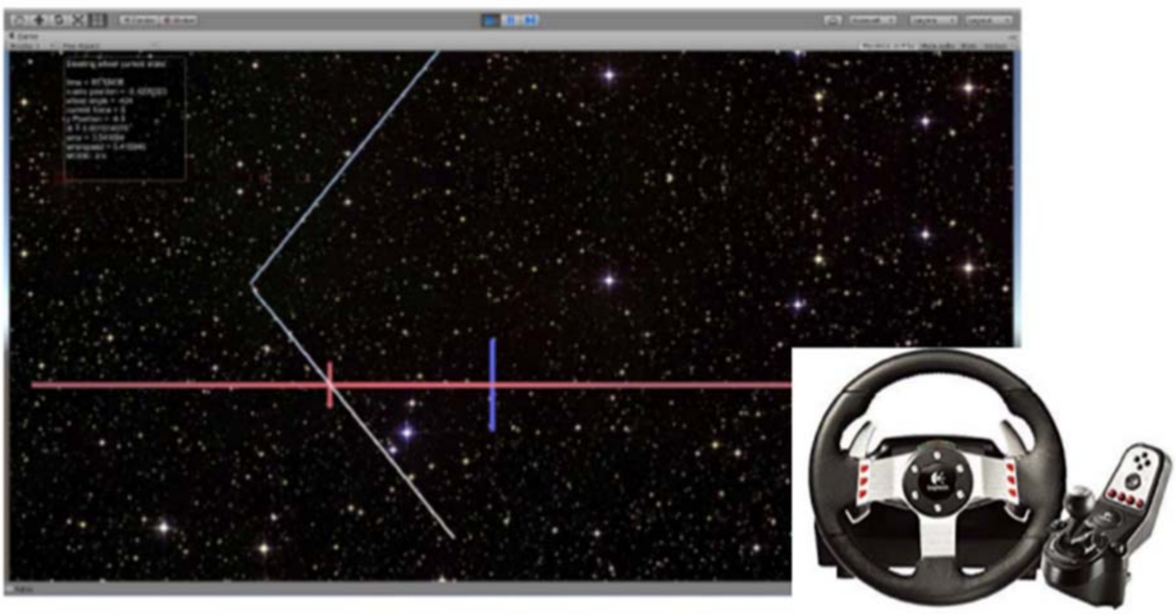
Analysis of Human Sensorimotor Performance in Challenging Multitasking Control



Sung Hoon Choi
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Mentor: John C. Doyle

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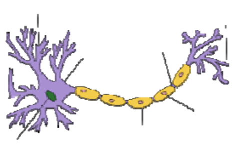
Question about human nervous system

Human nervous system (sensorimotor control)

Hardware level (neurons)



Tradeoffs in speed vs. accuracy (hardware limit)

Behavioral level

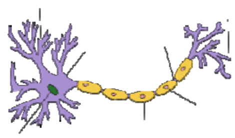
Better described by robust control than optimal control

1

Question about human nervous system

Human nervous system (sensorimotor control)

Hardware level (neurons)



Tradeoffs in speed vs. accuracy (hardware limit)

?

Behavioral level

Better described by robust control than optimal control

Behavioral Level

Motion tracking in presence of head motion

1. Oscillate your hand horizontally back and forth, increasing the frequency until the lines blur

2. Hold your hand still and shake your head horizontally at increasing frequencies until blurring occurs

Motion tracking in presence of head motion

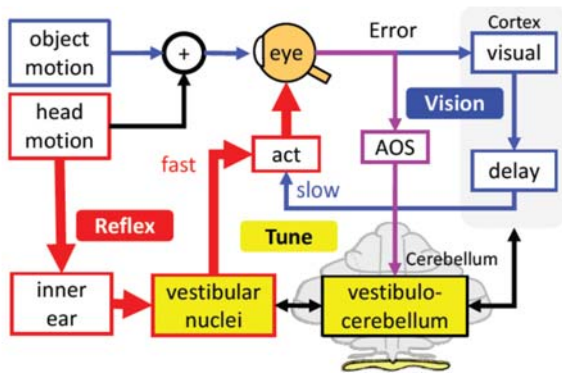
1. Oscillate your hand horizontally back and forth, increasing the frequency until the lines blur
   -> blurs in 1~2 Hz.

2. Hold your hand still and shake your head horizontally at increasing frequencies until blurring occurs
   -> blurs at much higher frequency

Motion tracking in presence of head motion

❖ Head motion is compensated via the **fast vestibulo-ocular reflex(VOR)**

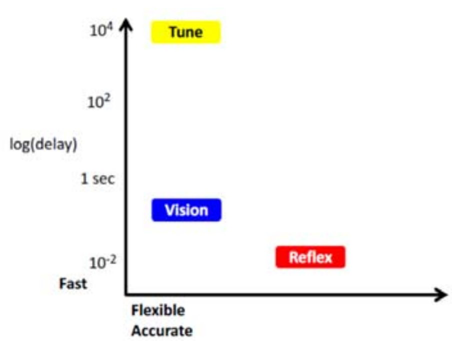
❖ Object is tracked via the **slow cortical visual feedback**



The gains sharing the eye muscle must match. Gains are tuned by cerebellum, vestibular nuclei, and auxiliary optical system

Motion tracking in presence of head motion

Fast and accurate visual performance is achieved with parts that are either fast or accurate **but not both!**



Layered controllers

The control system is **layered** by independent vision and reflex layer controllers

Layer 1 (vision) — **Advanced planning: slow and small error**

Tuning and learning needed for coordination

Layer 2 (reflex) — **Delayed reflexes: fast and large error**

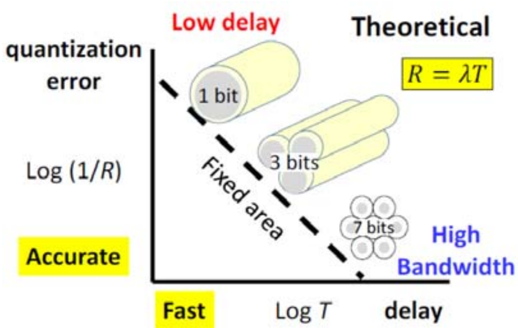
Hardware Level (neurons)

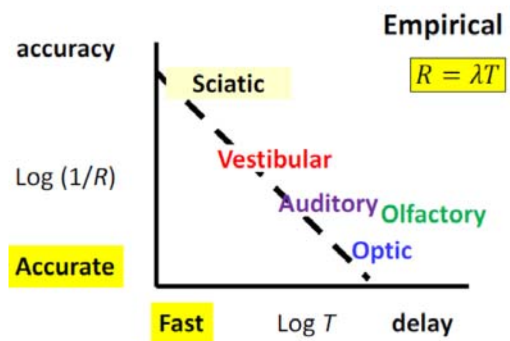
Hardware (neurons)

Heterogeneity in size and number of axons

Propagation **speed** of action potential ∝ axon's **diameter**

Signaling **bandwidth** ∝ **number** of axons





Hardware (neurons)

Heterogeneity in size and number of axons

Propagation **speed** of action potential ∝ axon's **diameter**

Signaling **bandwidth** ∝ **number** of axons

Hardware tradeoff between accuracy and speed

$$R = \lambda T$$

R: number of bits (bandwidth)
T: signaling delay

Behavioral Level

Control theory to connect the components

Hardware Level

Control Theory

Assume

The human sensorimotor composed of
- Sensors (eyes, inner ear)
- Communication Components (cranial and spinal nerves of CNS)
- Controllers (in CNS)
- Actuators (muscle/limb)

Model

$$P:\ x(t+1) = ax(t) + w(t - T_w) + R[u(t - T_u)]$$

$$C:\ u(t) = K(x(0:t), w(0:t), u(0:t-1))$$

$x(t) \in \mathbb{R}$: a scalar deviation between desired and actual muscle state
$w(t) \in \mathbb{R}$: a disturbance
$u(t) \in \mathbb{R}$: a scalar control action aimed to modify the actual muscle state

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Hardware Tradeoff

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Optimal cost

$$\begin{cases} \sum_{i=1}^{|\tau|} |a^{i-1}| + |a^{|\tau|}|(2^R - |a|)^{-1} & if\ \ \tau < 0 \text{ (delayed reaction)} \\ (2^R - |a|)^{-1} & if\ \ \tau \geq 0 \text{ (advanced warning)} \end{cases}$$

$\tau := T_w - T_u$: net warning
R : number of bits (neuron)

Control Theory

Assume

The human sensorimotor composed of
- Sensors (eyes, inner ear)
- Communication Components (cranial and spinal nerves of CNS)
- Controllers (in CNS)
- Actuators (muscle/limb)

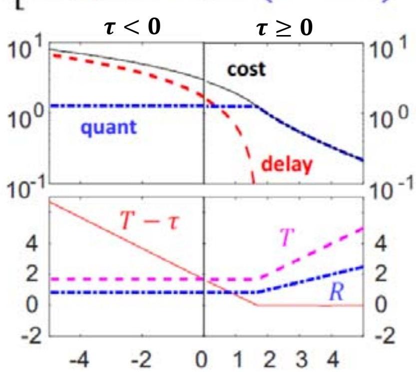
Optimal cost (Let $a = 1$)

$$\boldsymbol{Max}[\mathbf{0}, \boldsymbol{T} - \boldsymbol{\tau}] + (\mathbf{2}^{\boldsymbol{\lambda T}} - \mathbf{1})^{-\mathbf{1}}$$

T : Signaling Delay
τ : Net warning

Control Theory

$$\min_T \left[\max(0, T-\tau) + \left(2^{\lambda T} - 1\right)^{-1}\right]$$



Delayed reaction($\tau < 0$) - Reflex

Delay term dominates the overall cost.

Optimal nerve size should
sacrifice bandwidth in order to minimize delay!

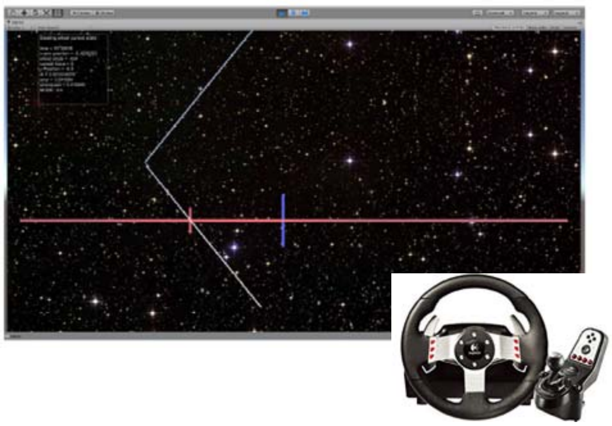
Advanced warning($\tau \geq 0$) - Vision

Quantization term dominates the overall cost.

Optimal nerve size should
sacrifice speed in order to maximize bandwidth!

Experimental platform

Experimental video game platform



Purposes

Quantify if the theory correctly predicts planning performance as a function of advanced warning

Quantify how close to optimal are humans in multiplexing planning and reflex tasks

Experimental platform

Experimental video game platform

Experiment goes through three scenarios

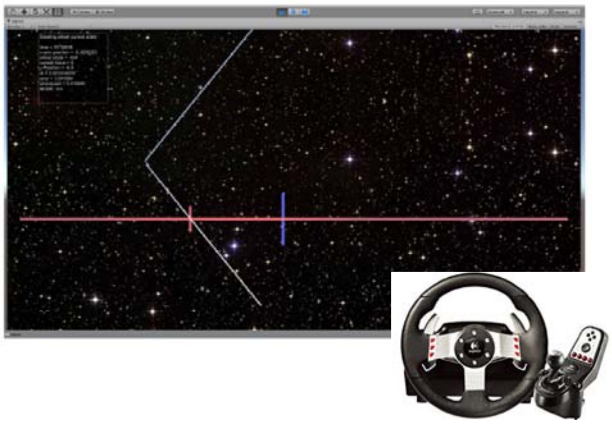
Bumps: Track a constant track subject to force disturbances on the wheel

Trails: Track moving trail while having look-ahead but no forces

Trails with Bumps: Track a moving trail while there are force disturbances on the wheel

Experimental platform

Experimental video game platform



Experiment goes through three scenarios

Bumps: Track a constant track subject to force disturbances on the wheel ➡ **Reflex!**

Trails: Track moving trail while having look-ahead but no forces ➡ **Vision!**

Trails with Bumps: Track a moving trail while there are force disturbances on the wheel ➡ **Multiplex!**

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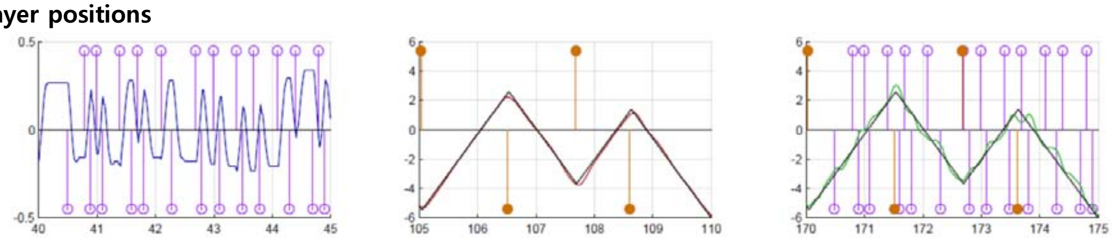
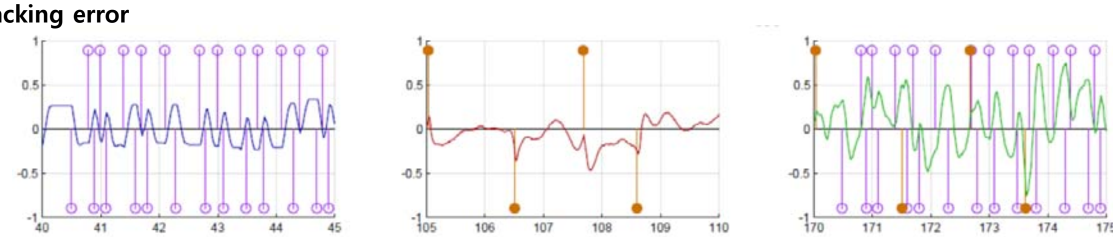
Experimental platform

Player positions



Bump **Trail** **Trail with bumps**

Tracking error



Bump **Trail** **Trail with bumps**

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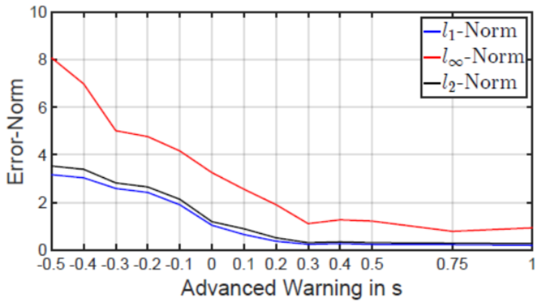
Experimental platform

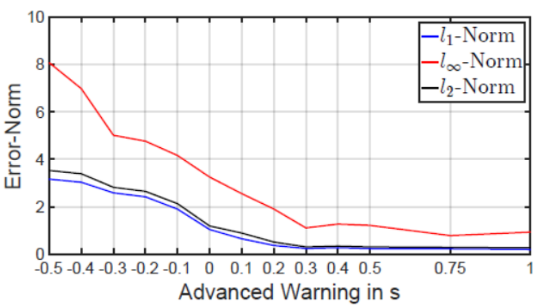


Optimal cost (Let a = 1)

$$Max[0, T-\tau] + (2^{\lambda T}-1)^{-1}$$

T : Signaling Delay
τ : Net warning

Experimental platform



Match strikingly well!

Optimal cost (Let a = 1)

$$Max[0, T-\tau] + (2^{\lambda T}-1)^{-1}$$

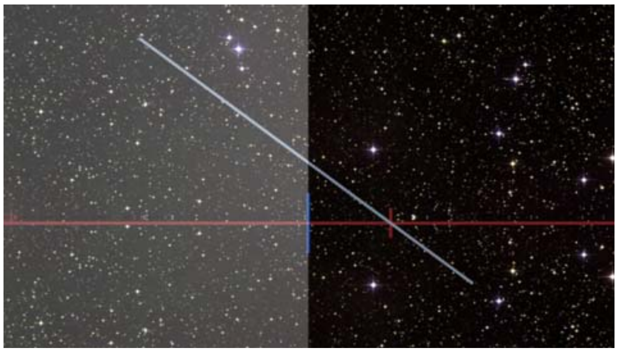
T : Signaling Delay
τ : Net warning

For τ < T, the error increase linearly with τ.

T ≈ 250ms (typical visual delay for humans)

Experimental platform - Upgraded

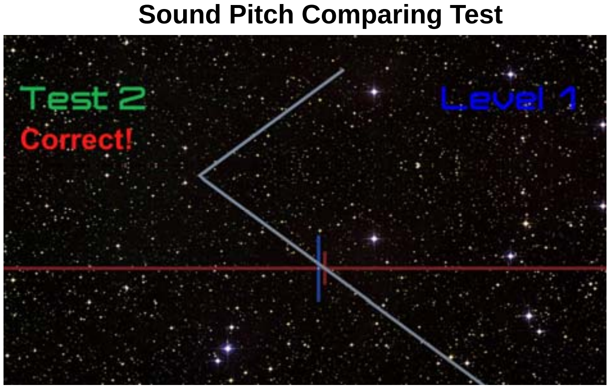
Flash Test

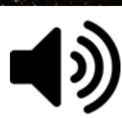


Color Contrast Test

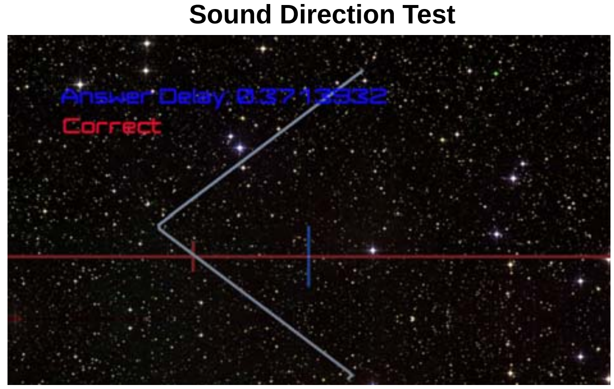
Experimental platform - Upgraded

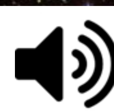
Sound Pitch Comparing Test





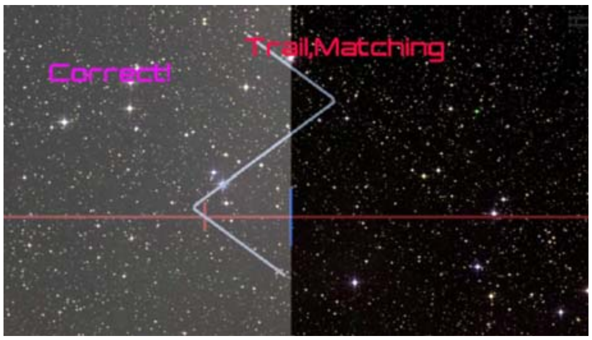
Sound Direction Test





Experimental platform - Upgraded

Matching Test = flash + sound test



Are flash and sound coming from same side?

- Flash: Left Sound: Left → Press Left button
- Flash: Right Sound: Right → Press Right button
- Flash: Left Sound: Right / Flash: Right Sound: Left → Don't press anything

Experimental platform - Upgraded

Upgraded game routine

Round 1 (Drive)	Bump	Trail	Trail with Bump
Round 2 (Drive,Flash)	Bump + Flash Test	Trail+Flash Test	Trail with Bump + Flash Test
Round 3 (Drive,Match)	Bump + Matching Test	Trail+Matching Test	Trail with Bump + Matching Test

Experimental platform - Upgraded

First trial

Experimental platform - Upgraded

Second trial

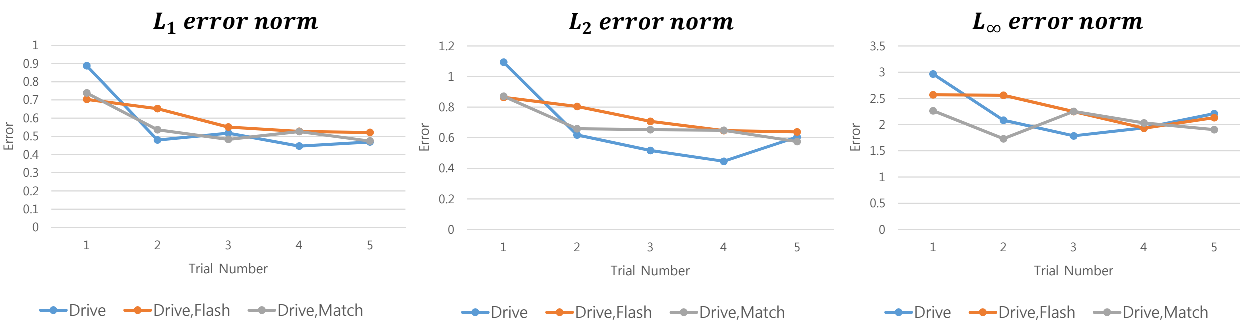
Experimental platform - Upgraded

First trial

Second trial

Experimental platform - Upgraded

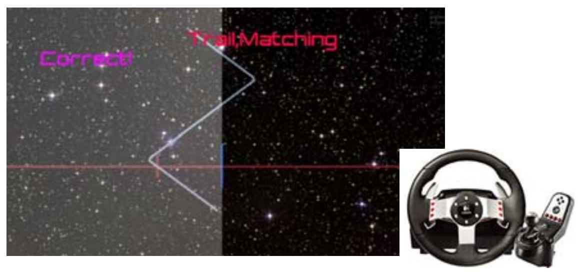
Error Norms vs Trial Number



Future Goals

Add more basic tasks(visual, auditory) that do not interfere.
➡ Push the multitasking performance to limits.

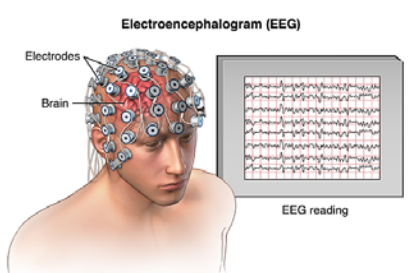
Do experiments with subjects to study how people learn.
➡ Come up with a theory to explain human learning.

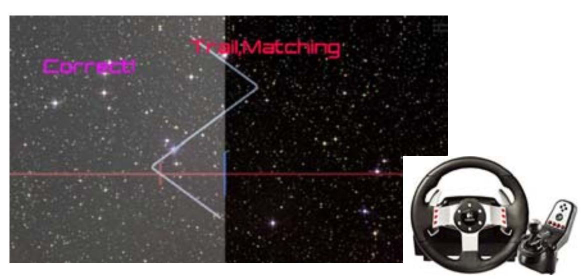


Future Goals

Use the game platform with EEG to study brain activity as tasks and multitasking changes, and as learning changes.

Identify the cortical sources that are active during different phases of the task.





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2. N. Matni and J. C. Doyle, "A theory of dynamics, control and optimization in layered architectures," in *American Control Conference (ACC)*, July 2016.

3. J. C. Doyle, Y. Nakahira, Y. P. Leong, E. Jenson, A. Dai, D. Ho and N. Matni, "Teaching control theory in high school", 2016 IEEE Conference on Decision and Control

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