Project Review: Teleoperation and time delays

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1. Study the invariance in the shift in control strategy from continuous control to move-and-wait as a function of latency and control difficulty.
2. Develop a theoretically understood way of introducing measureable levels of control difficulty using misalignment between display and control axes . (From an explanation of some results of Experiment 1)
3. Use this understanding to study the interaction of control difficulty and system latency.
4. Conducted Experiment 3 to calibrate our imposition of control difficulty using more representative control rotations.
5. Conducted Experiment 4 to directly study interaction of control difficulty with latency.
6. Results suggest a way to generalize latency requirements across control difficulties that should aid establishment of standards for managing latency in teleoperation.

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** San José State University Foundation

Measuring and Explaining the Misalignment Effect Function (MEF) and its Interaction with System Latency

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Explaining some geometric bases of user control difficulties caused by generalized misalignments between display and control axes as occur during teleoperation.

1. Project Review
2. Misalignment Effect Function (MEF)
3. Definition and measurement of a spatially generalized MEF
4. Features of the generalized MEF
5. Control rule to explain the first part of the MEF
6. Interactions with time delays
7. A geometric approach to additional trajectory analyses

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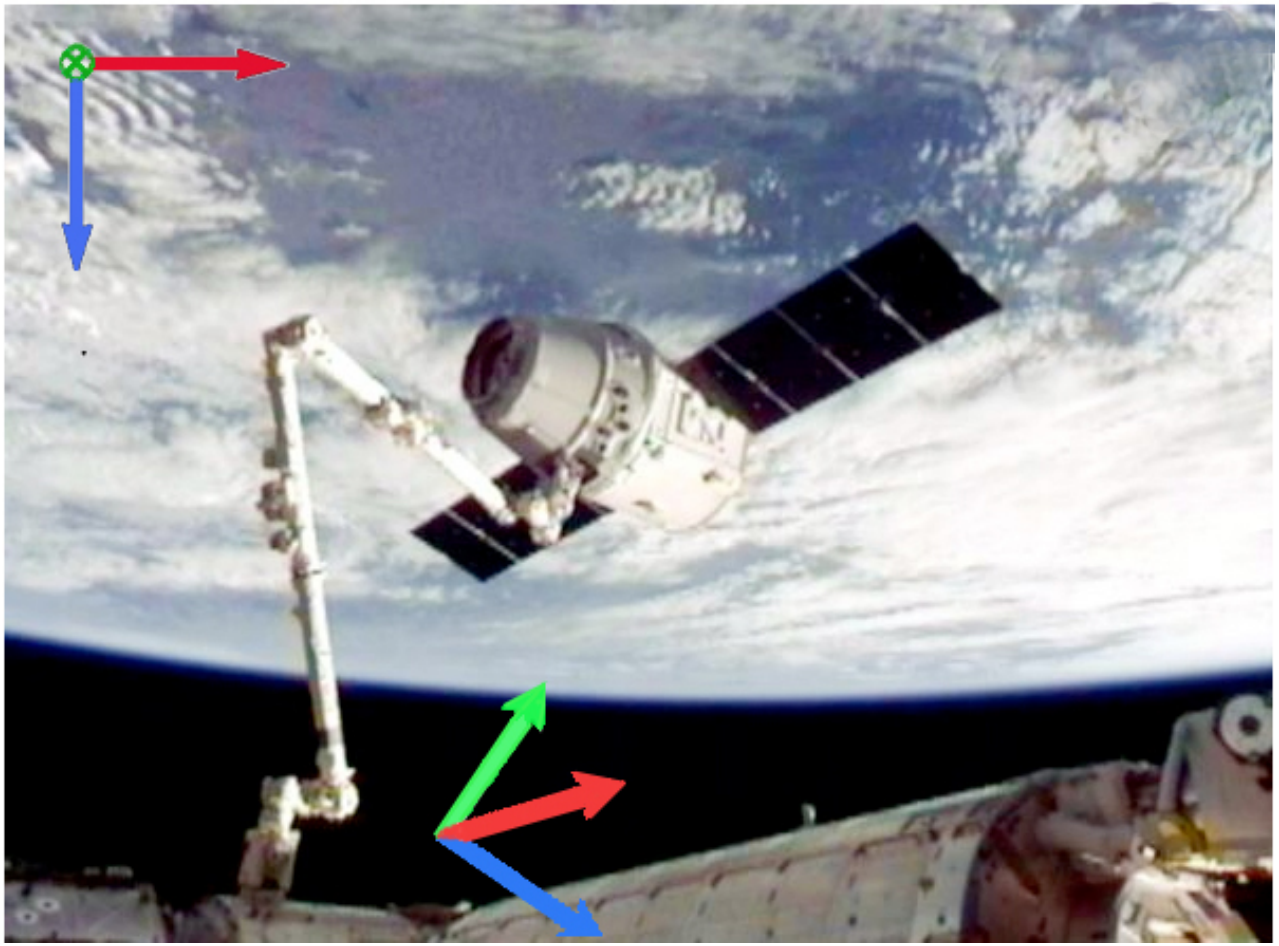
Space Station Arm Captures Dragon

Viewing
co-ordinates



Control
co-ordinates

Some Previous Research

Helmholtz, H. (1867) *Handbook of Physiological Optics*

Fitts, P. M . & Simon, C.W. (1952) Some relations between stimulus patterns and performance in a continuous dual-pursuit task

Smith, K.U. and Smith W.M. (1962) Perception and Motion: an analysis of space structured behavior: review of several years of previous work on control misalignments

Bernortat, R.K. (1970) Rotation of visual reference systems and its influence on control quality.

Guiard, Y. (1987) Asymmetric division of labor in human skilled bimanual action: a kinematic chain model.

Cunningham H.A. et al (1989) Aiming error under transformed spatial mapping reveal spatial structure of visual motor maps w/ Vadi and Pavel

Ellis, S.R., Tyler, H., Kim, W. S. & Stark, L. (1992) three dimensional tracking with misalignment between display and control axes, decomposition of visual and sensorimotor influences.

Stassen H.G. & Smets, G.J.F. (1995) Telemanipulation and telepresence, a review.

Hinkley, K., Paush, R., Profet, R. Patten,J. & Kassell, N. (1997) Cooperative bimanual control helpful role of physical props.

Macedo, J.A., Kaber, D.B., Endsley, M.R., Powanusorn, P., Myung, S. (1998) The effect of automated compensation for incongruent axes on teleoperator performance.

Abeele, S. & Bock, O. (2001) Sensorimotor adaptation to rotated visual input: different mechanisms for small versus large rotations

Ellis, S.R. & Adelstein (2009) Kinesthetic compensation for sensorimotor rearrangements.

Misalignment Effect Function Definition (MEF)

The Misalignment Effect Function describes the relative decrement in interaction with spatially presented objects due to a rotation between a user's display coordinates and those with which they control the object.

Measurement Issues

Goal: to determine the geometric basis of control difficulties caused by the unusual motion due to rotated control coordinates.

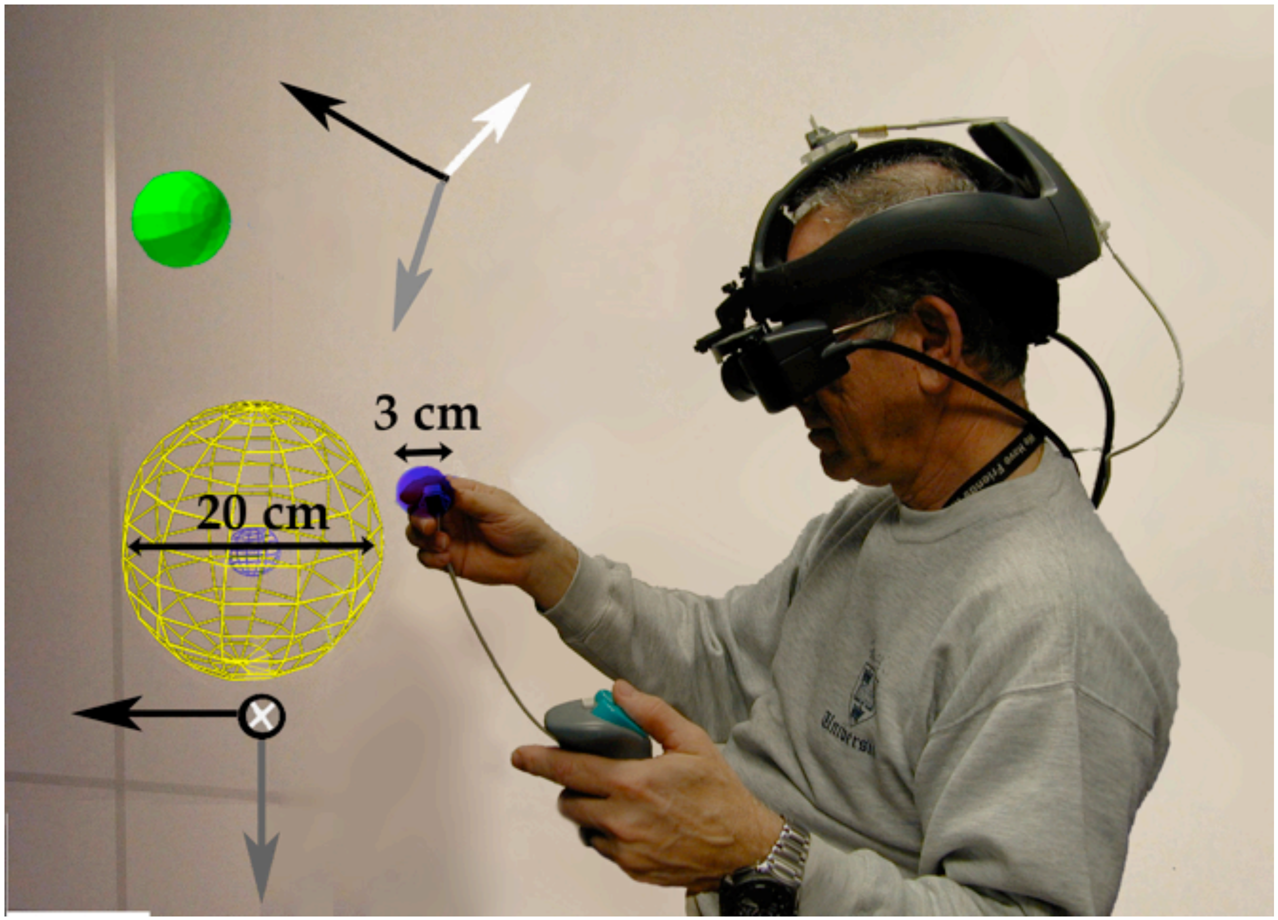
- Predict control difficulty for arbitrary control rotations & movement directions
- Use this understanding to stress control strategies that shift with latency

• Environmental
- Study generalized movement and rotation and rotation to avoid isotropic bias
- Avoid effect masking due to environmental or other cueing

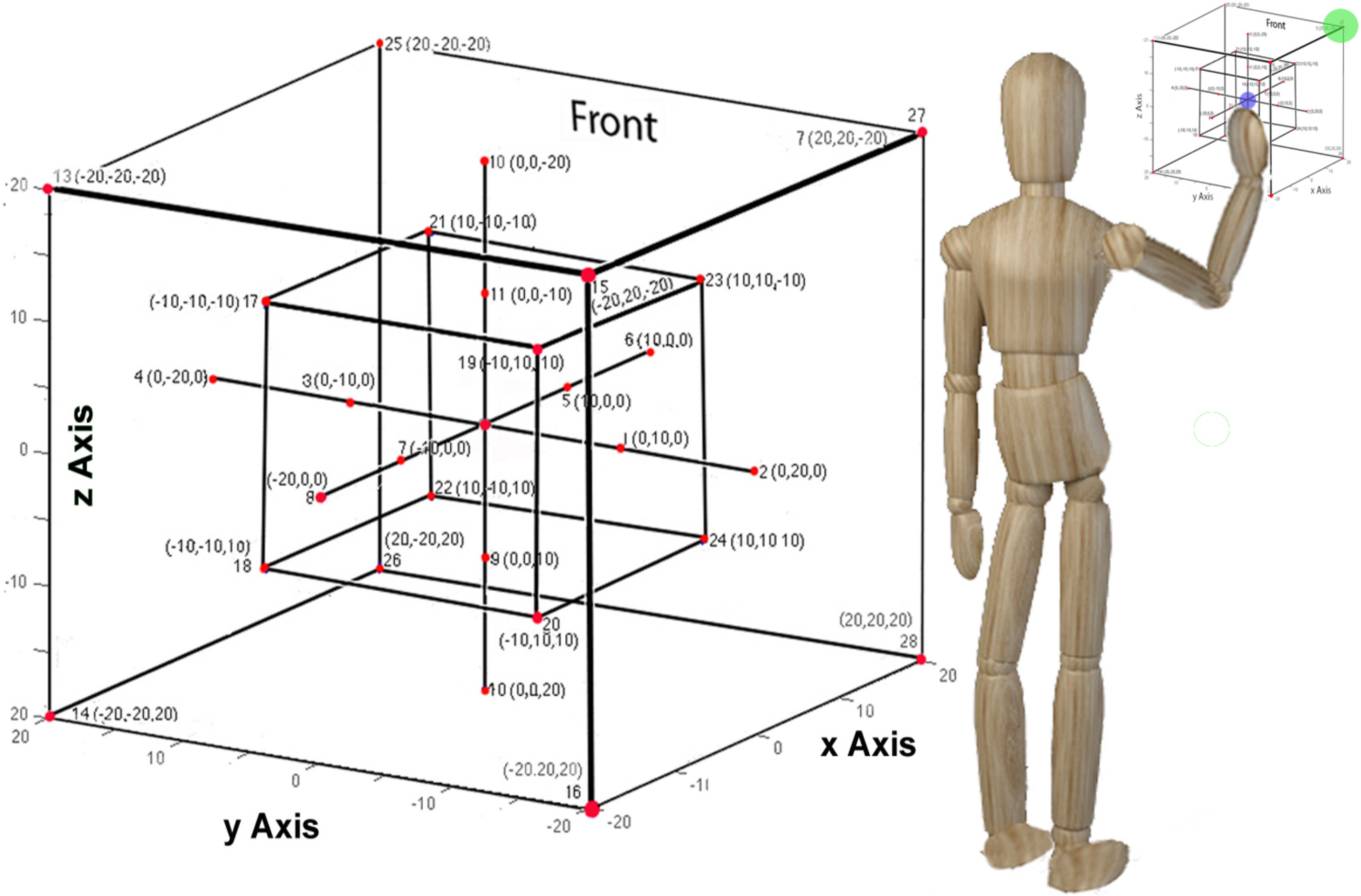
• Participants
- Use user-produced ”natural” placement movements
- Account for potential large inter-subject ability differences
- Minimize or mitigate training and sequence effects

• The dependent measures
- Select task with accessible geometric structure
- Choose measure with potential practical significance in closed loop response
- Identify a natural, theoretically based measure if possible

Task (exocentric view)

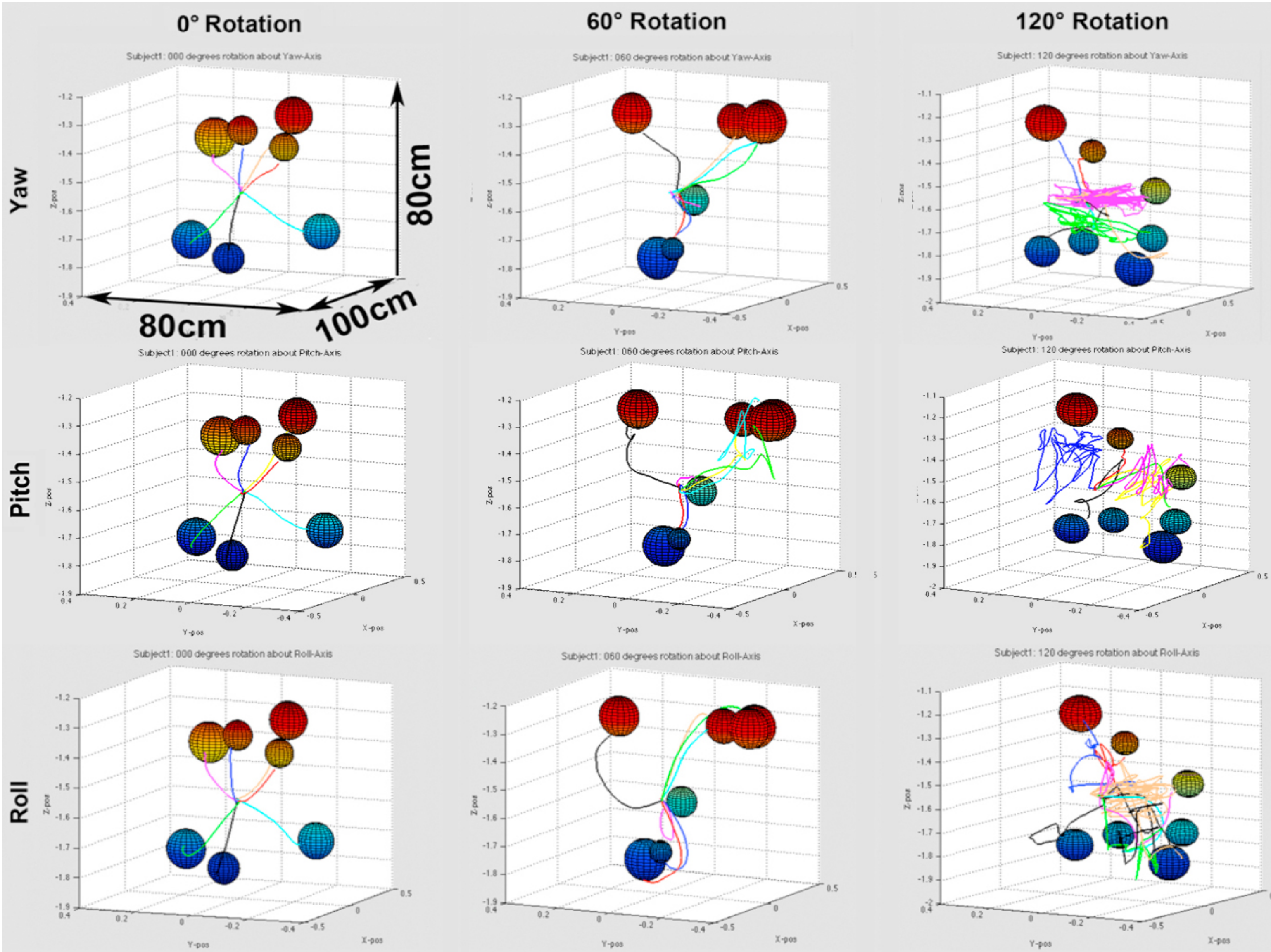


Targets



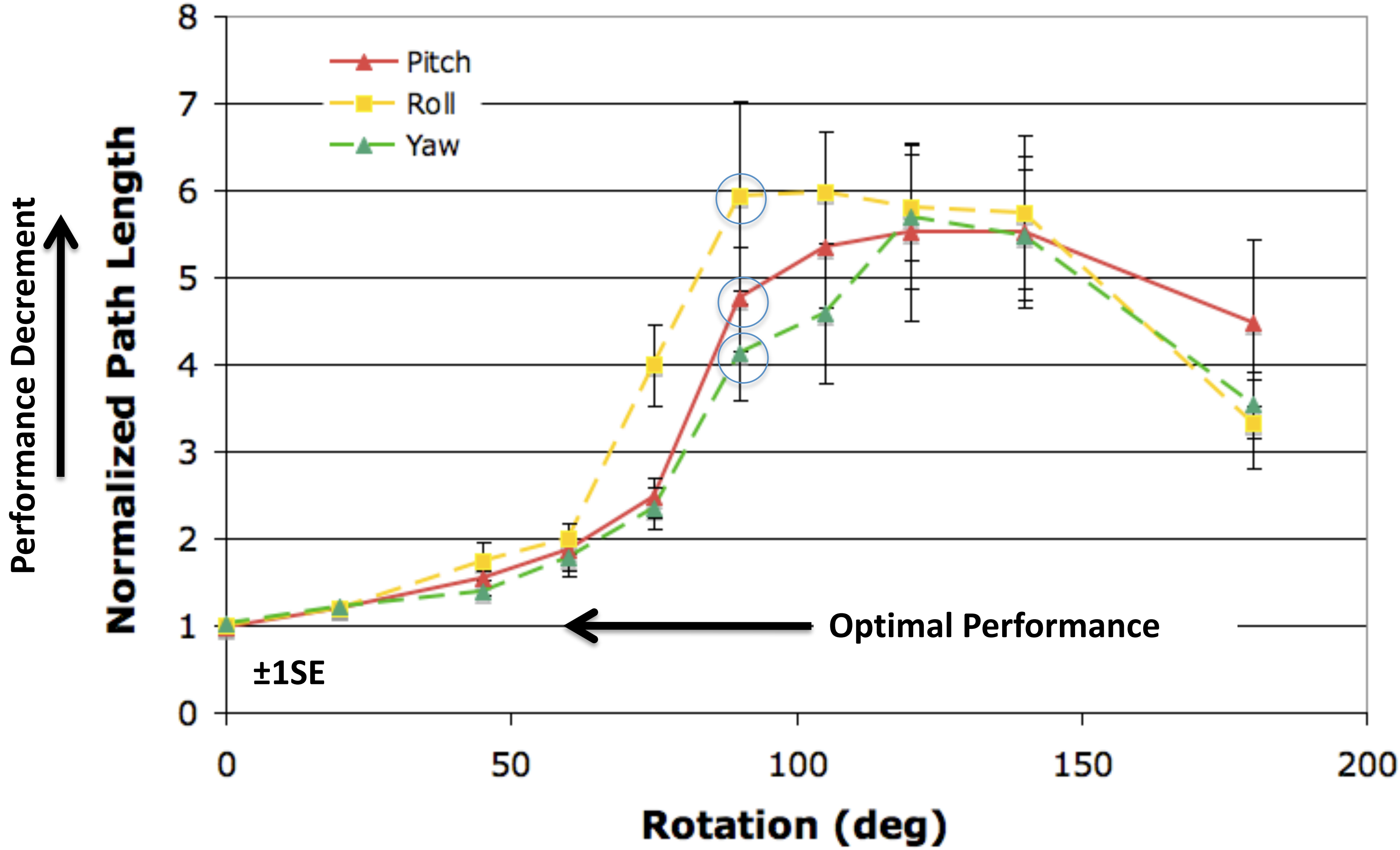
Front
25 (20,-20,-20)
27
7 (20,20,-20)
13 (-20,-20,-20)
10 (0,0,-20)
21 (10,-10,-10)
15
(-20,20,-20)
23 (10,10,-10)
(-10,-10,-10) 17
11 (0,0,-10)
6 (10,0,0)
19 (-10,10,10)
4 (0,-20,0)
3 (0,-10,0)
5 (10,0,0)
1 (0,10,0)
2 (0,20,0)
7 (-10,0,0)
(-20,0,0)
8
22 (10,-10,10)
24 (10,10 10)
(-10,-10,10)
18
(20,-20,20)
26
9 (0,0,10)
20
(-10,10,10)
(20,20,20)
28
10 (0,0,20)
14 (-20,-20,20)
(-20,20,20)
16
z Axis
y Axis
x Axis

Sample Trajectories

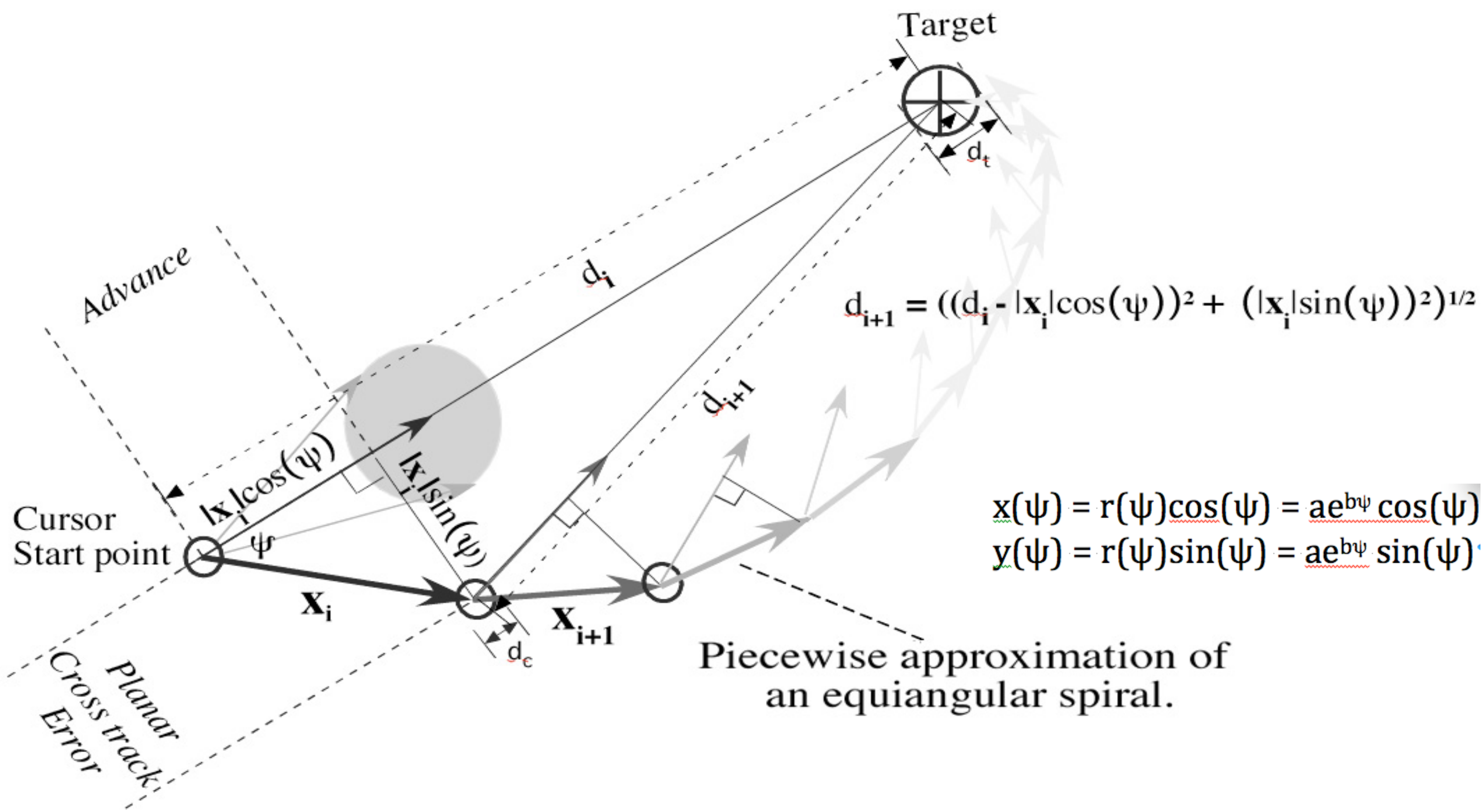


$$ID = \log_2\left(\frac{2D}{W}\right) = 3.5$$

Most Natural Response Measure

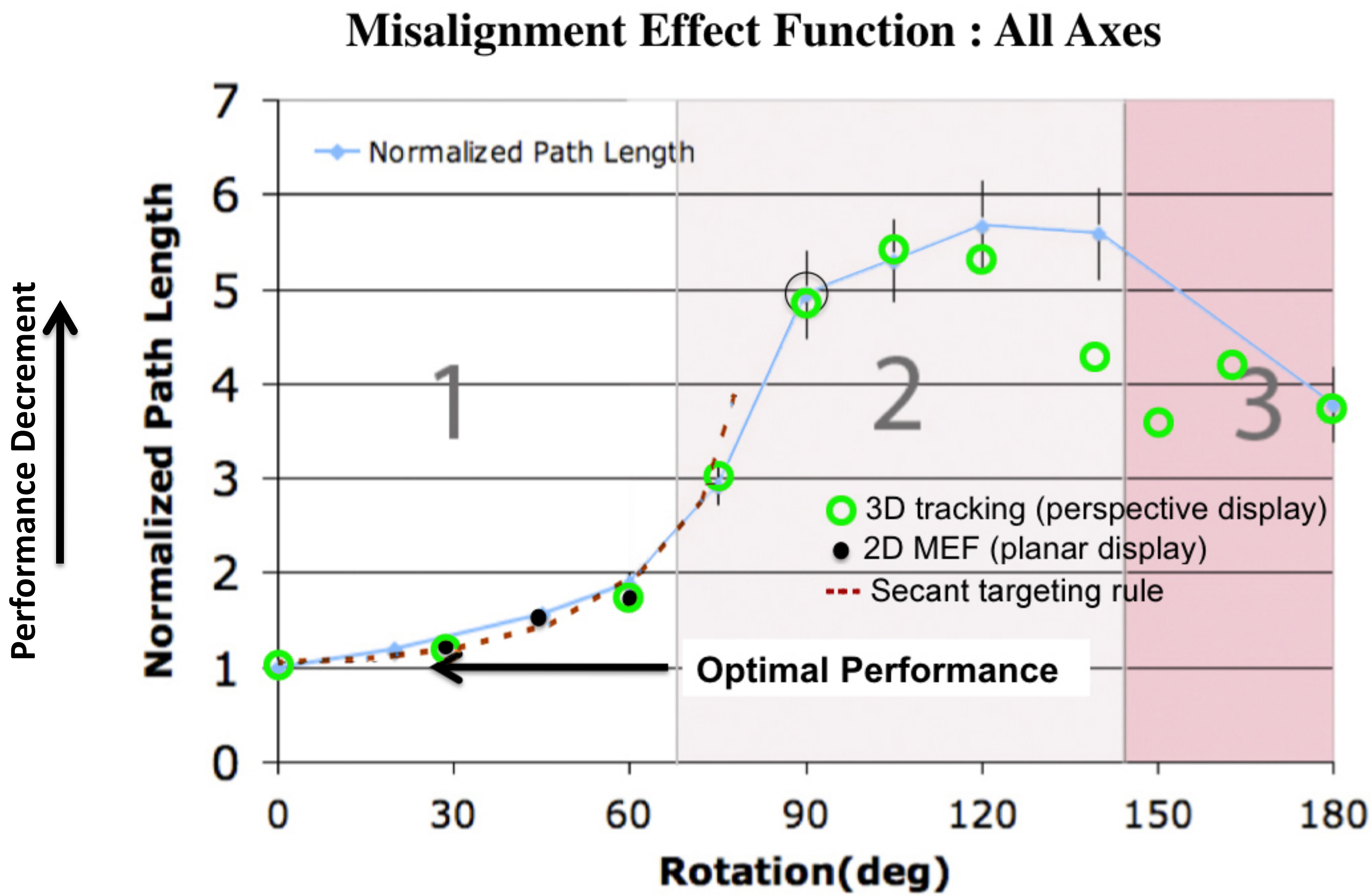


Principal Analytic Element



Targeting rule: Set current kinesthetic direction, $\mathbf{x}_{i+1}$ equal to movement start visual direction, $\mathbf{x}_{i+1}$

$$nPL = \sum_{n}^{i} |\mathbf{x}_i| / d_i \text{ and } |\mathbf{x}_i| << d_i \text{ so } \sum_{n}^{i} |\mathbf{x}_i|\cos(\psi) \sim d_i \text{ and } nPL \sim 1/\cos(\psi)$$



Misalignment Effect Function : All Axes
Normalized Path Length
Performance Decrement
Rotation(deg)
0
1
2
3
4
5
6
7
0
30
60
90
120
150
180
1
2
3
Optimal Performance
3D tracking (perspective display)
2D MEF (planar display)
Secant targeting rule

Experiment 3 with more Representative Rotation

Subjects selection/screening: < 1’ stereo resolution, Measured IPD
10 S, 20-64 yrs, 8 M, 2 W, unpaid x

Task: Movement of spherical cursor to touch spherical targets randomly positioned at varied distance in octants surrounding start point with constant Fitts’ Index of Difficulty

Hardware & software: High performance Rockwell-Collins SR80™ HMD-based customized, calibrated Virtual Environment system, head/hand tracking@120Hz, 25 ms measured stable system latency, 60 Hz stereo rendering. In-house software developed by R. Jacoby using C++ and WorldToolKit

Familiarization: 15-25 minute familiarization to establish baseline “normal” movement, inter pupilary distance adjustments, verification of stereo, task understanding, movement goal & task elements.

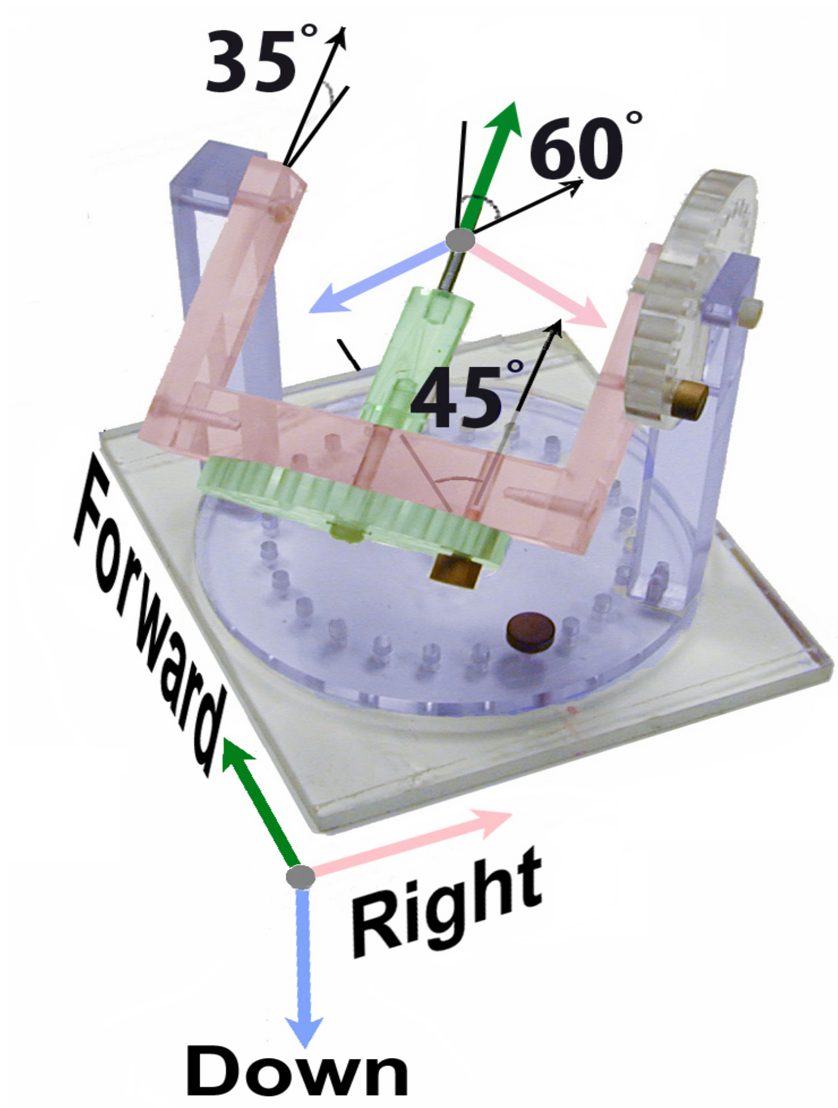
Design and Implementation: Independent variables: “Rotation representativeness”: Yaw: ±45°, Pitch:+35°, Roll: 0, ±30, ±60, ±90°, Blocks of fixed rotations of 10 movements including 3 initial, excluded warm up movements, Near & Far targets: 11 cm, 22 cm. Targets in all possible octants, Same targets for all, Randomized blocks design.

Planned Dependent Measures: Normalized Path Length

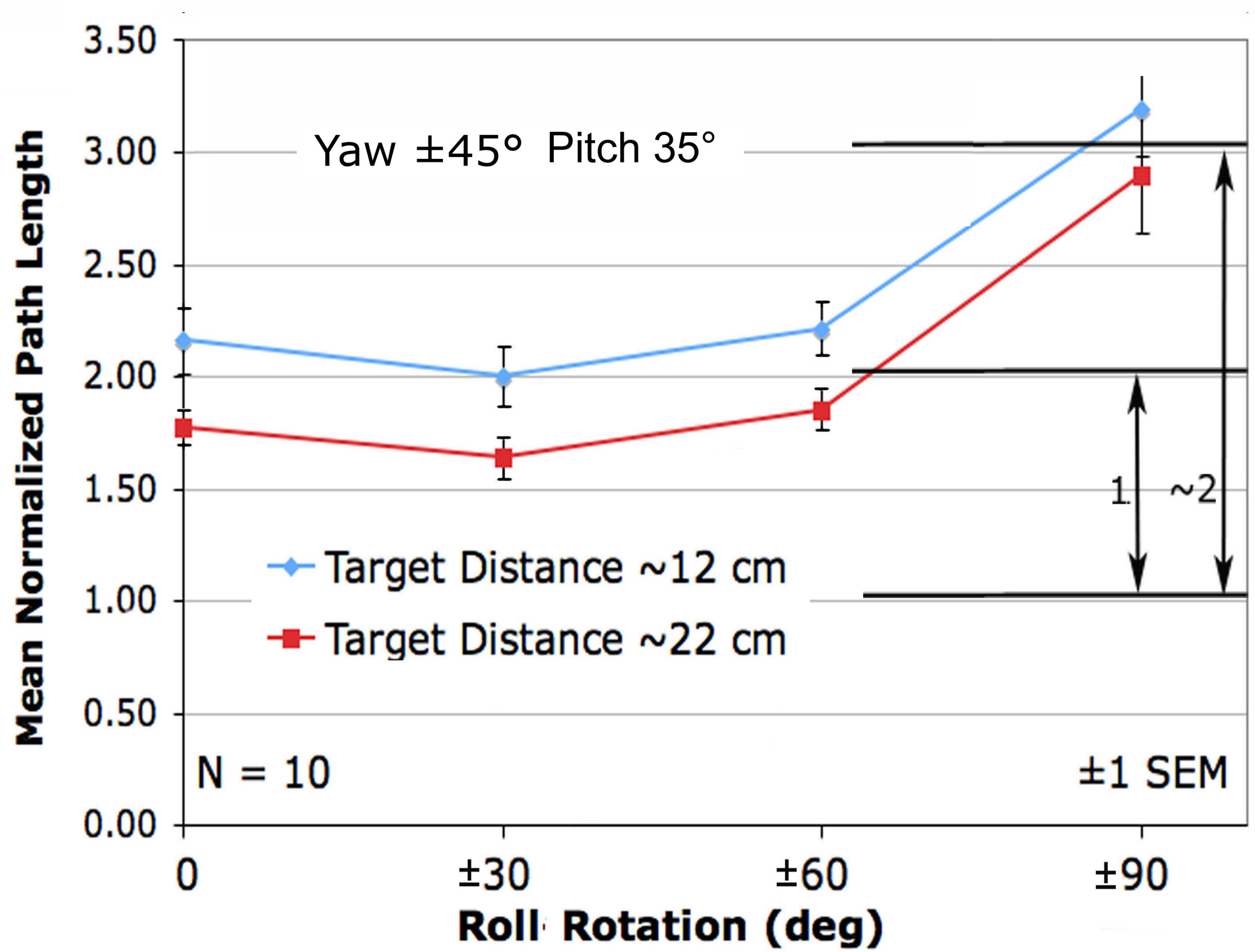
Analysis: Rotation X Target_Distance X Subjects, ANOVA

More Generalized (Complex?) Rotation

Euler Rotations Embodied in a Helmholtz Gimbal



Experiment with More Generalized (Complicated ?) Rotation 3

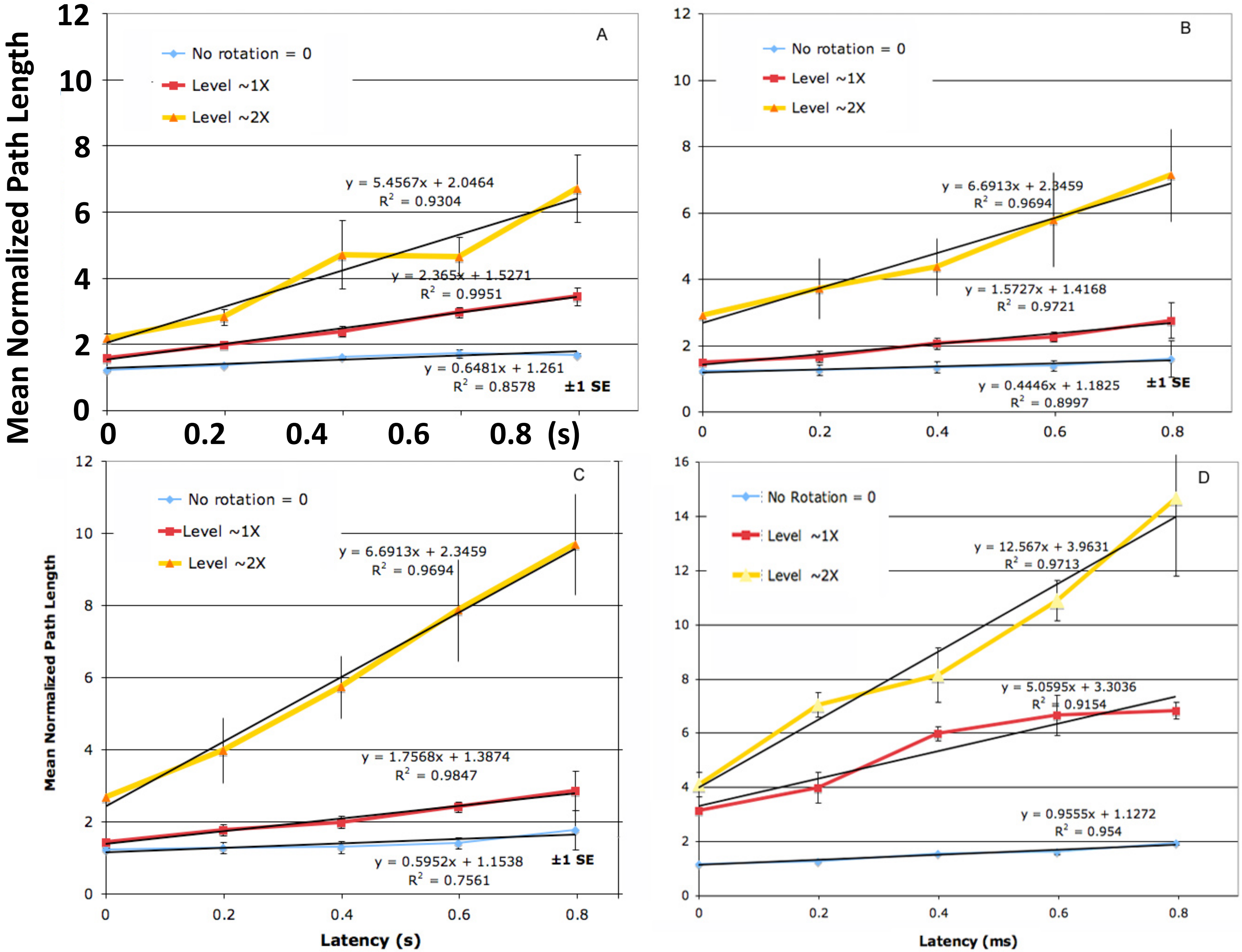


All subjects get same targets in random orders.   Fitts' ID = 3.3

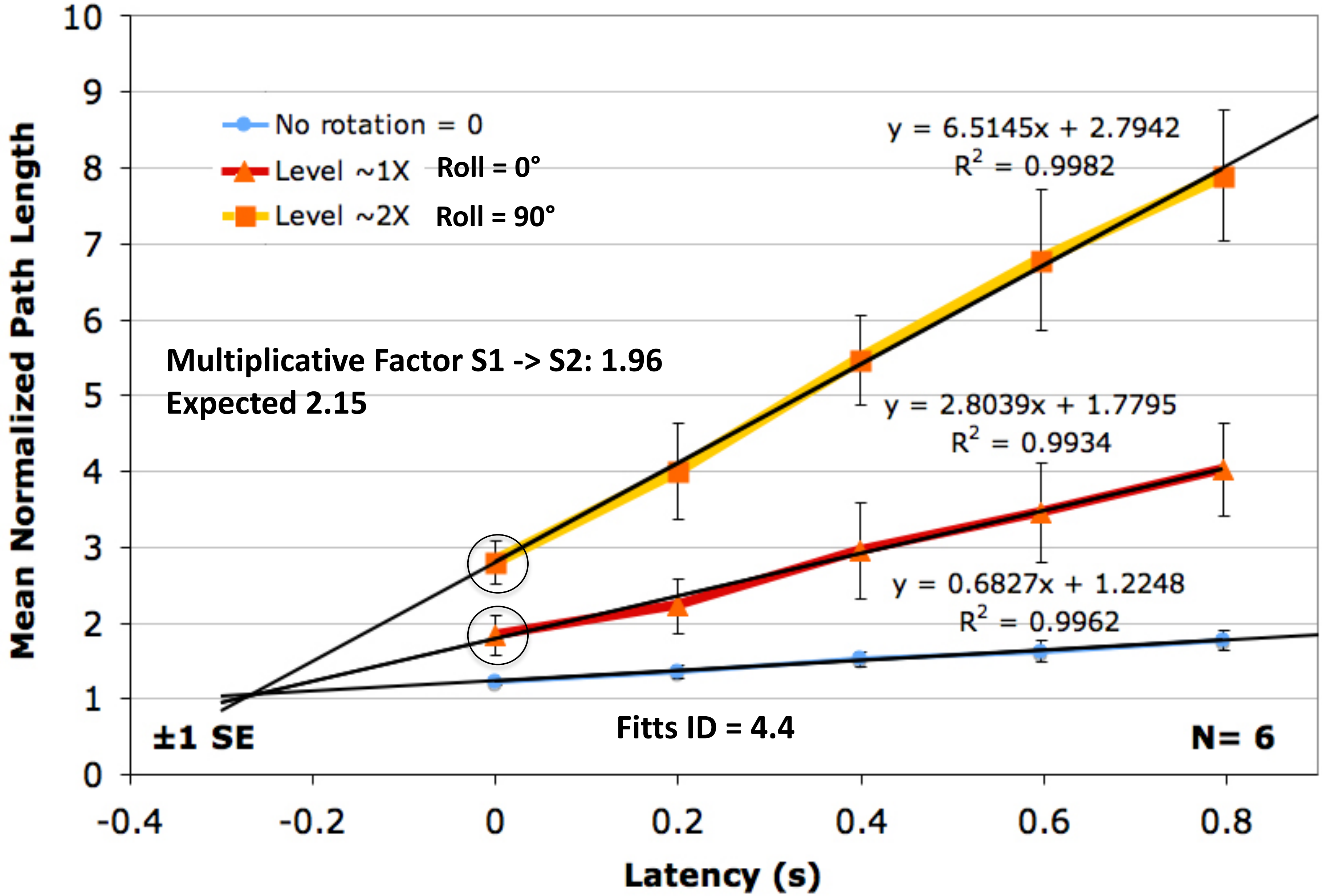
Experiment 4 with Time Delay

1. Single target distance 16.5 ±5% cm
2. 18 targets per Block
   Three warm-up targets
   14 randomly ordered targets on approximate symmetry axes of cube (± 7°)
   1 marker for manual latency change
2. Three stress/difficulty levels:
   No rotation,
   Level 1 ±45°, 35°, ±0 (yaw, pitch, roll)
   Level 2 ±45°, 35°, ±90
3. Five delay increments (above system minimum ~30 ms)
   0, 0.2, 0.4, 0.6 0.8 (s)
4. Adjusted Fitts ID=4.4 to bracket presumptive strategy shift and control fatigue.
5. Randomized selection/ordering of latency-difficulty pairing for each 18 target block
6. Experimental Phases
   Screening for stereo and IPD measurement
   HMD and task familiarization
   Five blocks of 14 experimental targets: 0 latency increment and 0° rotation
   Twenty blocks with randomly ordered 5 levels of latency
   Forty randomized of blocks of pairing 3 difficulty levels with 5 latency levels
7. Three-four hours over 2-3 days

Experiment 4 with Time Delay 2



Experiment 4 with Time Delay 3



Summary

1. Accurately measured and partially explained the Misalignment Effect Function (MEF) arising in manual telerobotics..
2. A targeting model in which users move to a target current making **kinesthetic direction equal to current visual direction** leads to a simple, spontaneously arising, (new?) geometric law of part of the MEF that requires no free parameters.
3. **$MEF(\Psi) = 1/\cos(\Psi) \pm < 5\%, \quad 0 \leq \Psi \leq 65°$** defines a **sec(Ψ) rule for** an equivalence class over movement velocity profiles.
4. Used understanding of the MEF and an experiment with more representative control rotations to select control difficulties to examine the invariance of control strategies shifts during increase latency.
5. Conducted an experiment revealing a multiplicative interaction between latency and control stress due to rotation
6. This finding provides a possible means to generalizing latency requirements across increasing task difficulty.
7. Further geometric analysis of the spherical geometry of rotation provide geometric basis for explaining counterintuitive performance effects in teleoperation.
8. Have identified control strategy shifts due to the interaction of latency and control stress but need further trajectory analysis to completely characterize it.
9. Found some evidence in generalized movement consistent with Crossman's successive approximation approach to explaining Fitts law.