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Motor Control and Motor Learning: Incorporating the Fundamentals into Clinical Practice

Jill Seale, PT, PhD, NCS

Learning Outcomes

After this course, participants will be able to:

- Outline at least one historical and one current motor control/motor learning theories/models.
- Identify at least two supporting or contradictory evidence for a given motor control/motor learning model.
- Identify at least three differences of the motor learning approach to other past and current treatment approaches.
- Identify at least four principles necessary for effective motor learning in persons with neurological injury, with focus on how the manipulation of practice and feedback maximize positive neuroplastic change and recovery.
- Identify at least three evidence-based models which integrate principles of motor learning.
- List at least five treatment strategies that incorporate practice and feedback in order to enhance motor learning and outcomes.

Historical Perspective of Motor Control Theories

"No one theory is universal in explanation of movement control… select pieces which are **evidence based** and **clinically relevant**, apply in **systematic fashion**, and **share with colleagues** "

– Perry SB, 1998

Motor Control Theories

- Description of unobservable structures and processes and their relationship to observable events
- Model of how movement is achieved
- Assessment and treatment approaches are driven or biased by the theoretical model
- Basic question: Who's in control?

Reflex Theory

- Sherrington's theory from late 1800s and early 1900s
- Complex movements explained by combined actions of individual reflexes – reflex chaining
- Movement is essentially the sum of reflexes
- Sensation is necessary

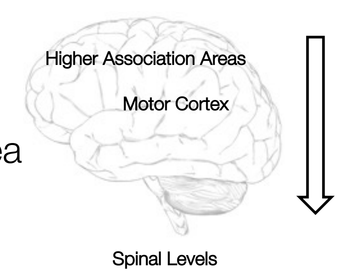
Reflex Theory Supporting Evidence

- Withdrawal reflexes
- Reciprocal inhibition
- Studies with mesencephalic cats

Reflex Theory Contradictory Evidence

- Reflexes can be "turned off" with supraspinal control
  - For the right motivation
  - Under certain conditions
- Sensory not needed for movement

Hierarchical Theory



- Brain as the supercomputer idea
- Top down model
- Reflex/hierarchical theory
  - Motor control is result of reflexes nested within hierarchy of CNS- Shumway-Cook, Woollacott, 2012

Hierarchical Theory Supporting Evidence

- Reflexes are controlled by the lower levels of this hierarchy and emerge when higher centers are damaged – Magnus, 1925
- Development of mobility in humans
  - Progressive appearance and disappearance of hierarchically organized reflexes
    - Schaltenbrand, 1928
- Maturation of infants
  - Motor development attributed to increasing control of higher centers
    - McGraw, 1945; Gesell, 1954; Gesell, Armatruda, 1947

Hierarchical Theory Contradictory Evidence

- How does this model explain the spinalized cats?
- Suppression of reflexes does not equate with normal movement
- Are some reflexes really integrated or just a product of peripheral constraints?

Motor Programming Theories

- Central motor pattern or motor program
- Explains how movements occurs in absence of sensory feedback
- Higher level motor programs representing actions in abstract terms; store rules for generating movements

Motor Programming Theories Supporting Evidence

- Locomotion in cats where both ascending and descending tracts were severed – Grillner, 1981
- Central Pattern Generators: neural patterns that are hardwired
- Handwriting examples – Bernstein, 1967

Motor Programming Theories Contradictory Evidence

- Too many degrees of freedom
- Lack of flexibility
- Impact of mechanical and environmental factors (context dependency)
- Cognitive requirements

Systems Theory

- Considering whole system, not just neural components of movement
- Viewed whole body as mechanical system
- Control of integrated movement distributed throughout many interactive, cooperative systems
- Hypothesized a hierarchical control which utilizes synergies to control body's multitude of degrees of freedom
  - Bernstein N, 1967

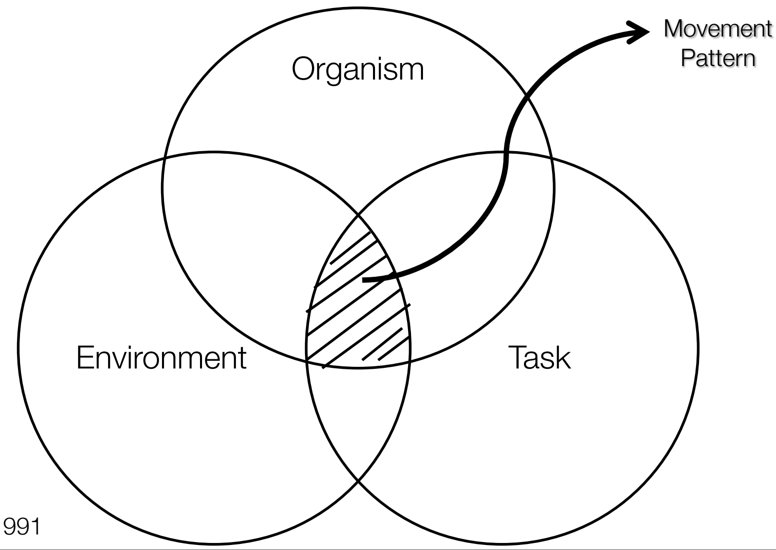
Systems Theory Limitations

- Not a lot identified… broadest, most applicable approach that we've discussed thus far
- Not a great deal of focus on interaction of human with environment - Shumway-Cook, Woollacott, 2012

Dynamic Action Theory

- Also known as Dynamic Systems Theory
- Motor tasks are problems to be solved and solutions are movement strategies generated by system – Higgins S, 1991
- Based on the principle of self organization
- Individual parts, when put together, act collectively in ordered way
- No need for instructions from higher centers
- Movement emerges as result of interacting elements
  - Shumway-Cook, Woollacott, 2012

Prescriptions v. Constraints



Newell, 1991

Dynamic Action Theory Supporting Evidence

- Normal development of gait
  - Thelen E, 1986
- Stepping behaviors in infants
  - Thelen et al, 1987
- Movement pattern transitions
  - Kelso et al, 1991; Scholz & Kelso, 1989
- Increase variability prior to emergence of more stable pattern
  - Woollacott and Shumway-Cook, 1990; Gordon, 1987; Kelso & Tuller, 1984

Dynamic Action Theory Limitations

- This theory down-plays role of nervous system
- Assumes desired movement strategy is available within system
  - Perry SB, 1998

Ecological Theory

- How motor systems interact with environment during goal directed behaviors
  - Gibson, 1966
- Use of perceptions to guide actions
- Motor control evolved so organisms could cope with environment
- First focus on how actions geared to environment
- Sensation not important… its perception

Ecological Theory Limitations

- Less focus on nervous system
- Not widely studied

Which Theory is RIGHT? Which Theory is BEST?

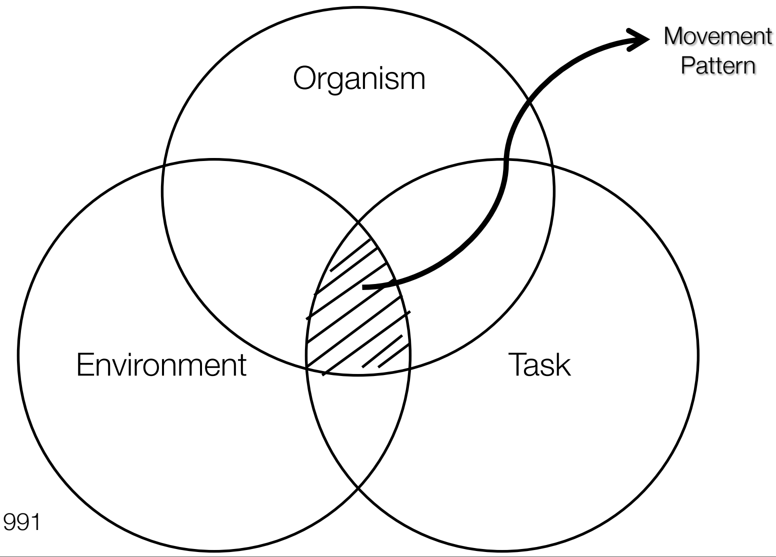
Motor Learning Defined

- Acquisition and/or modification of movement
- After injury, reacquisition of movement skills lost
- Processes associated with practice or experience leading to permanent changes in skill
  - Shumway-Cook, Woollacott, 2012

Concepts of Motor Learning

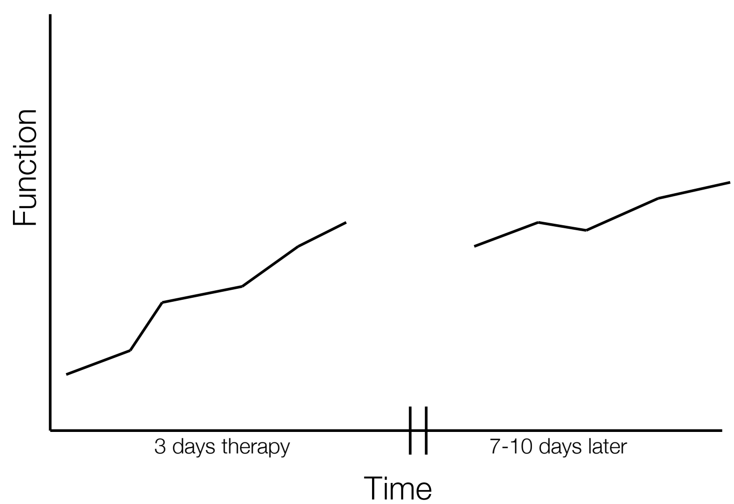
- Process of acquiring capability for skill
- Results from experience or practice
- Can't be directly measured; inferred from behavior
- Produces relatively permanent changes in behavior
  - Schmidt & Lee, 2005

Motor Learning Emerges from…



Newell, 1991

Performance versus Retention



Motor Learning Theories

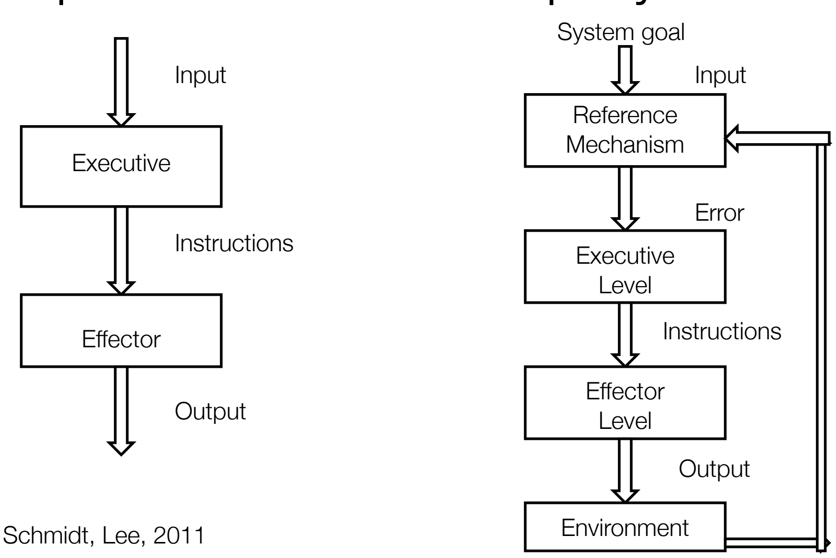
Schmidt's Schema Theory

- Open-loop control and generalized motor program
- Motor programs as generalized rules for specific types of movements, or schema
  - Schmidt, 1975, Schmidt & Lee, 2005
- Schema theory of ML is equivalent to motor programming theory of MC
- Predicted that variability of practice improved motor learning
- Limitations: Support is mixed for variable practice, doesn't account for immediate acquisition of coordination

More from Schmidt

- After making movement, 4 things available for storage in short term memory:
  - Initial movement conditions
  - Parameters used in generalized motor program
  - Outcome of movement (KR)
  - Sensory consequences of movement
- 2 schemas:
  - Recall schema (motor)
  - Recognition schema (sensory)
    - Summarized from Shumway-Cook and Woollacott, 2017

Open vs. Closed Loop Systems



Schmidt, Lee, 2011

Ecological Theory

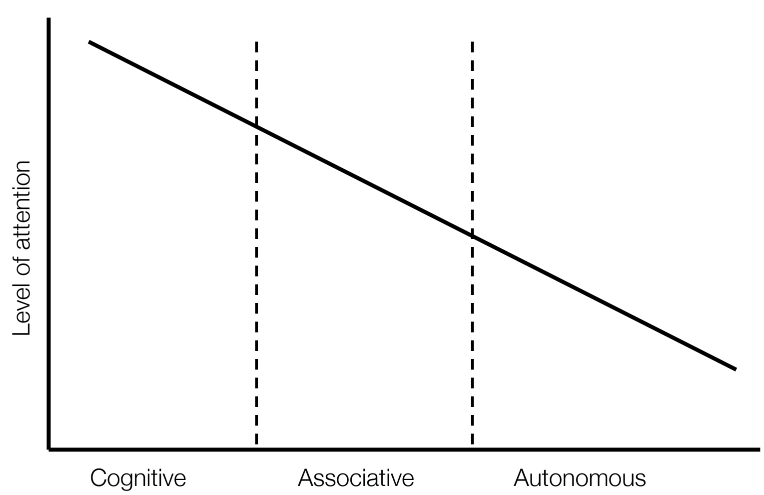
- Search strategies: search for optimal strategies to solve task, given task constraints
- Motor learning is task that increases coordination between perception and action
- Exploration of perceptual/motor workspace
- Perception: understanding goal, feedback, structures the search
  - Newell, 1991

Stages of Motor Learning

Fitts and Posner Three-Stage Model

- Cognitive stage:
  - Acquisition of knowledge
  - Trial and error stage
- Associative stage:
  - Refining of skill
  - Less variability
- Autonomous stage:
  - Automaticity of skill
  - Low degree of attention

Fitts and Posner Three-Stage Model



Bernstein's Three-Stage Model

- Key component is controlling or mastering degrees of freedom (DOF)
- Novice stage
  - Simplify movement to decrease DOF
- Advance stage
  - Gradual release of DOF
- Expert stage
  - Release of all DOF
    - Vereijken, Newell, et al, 1992

Gentile's Two-Stage Model

- Stage 1 goal: Develop understanding of dynamics of task
- Stage 2 goal: Refine the movement
  - Fixation
  - Diversification

2 Phases of Learning

- Fast phase
  - Initial, fast improvements
  - Seen in single session or first few sessions
  - Activation of striatum and cerebellum
- Slow phase
  - Slow, evolving
  - Moderate gains, progressing across multiple sessions
  - Motor cortex
  - Increase in number of synapses
    - Kleim JA et al, 2004, Karni et al, 1998, Ungerleider et al, 2002

Motor Learning Approach Versus Other Past and Current Treatment Approaches

Motor Relearning Program in Stroke

- RCT, matched pair
- 18, 2 hour sessions, MRP or Conventional
- Outcomes = Berg, TUG, FIM IADL, community integration questionnaire
- MRP showed better results in all but the TUG
  - Chan DY, Chan CC, Au DK, 2006

NDT vs Motor Relearning Programme

- Double blind study with 61 subjects
- Outcomes included measures of spasticity, volitional movement, and ADL
- Also looked at LOS, use of assistive devices
- Shorter LOS with MRL, as well as improved spasticity and volitional movement; no change in ADL
  - Langhammer B, 2000.

More recently

- RCT with patients with acute stroke
- Significantly improved function and quality of arm and hand movement with MRP as compared to Bobath.
- Results support that task oriented exercises promotes movement quality (This is BIG!)
  - Langhammer & Stanghelle, 2010

Bobath vs. Movement Science-Based Approach

- Bobath included more physiotherapy equipment, social conversation, assistance of another person
  - Manual strategies utilized
- MSB provided more detailed feedback, use of everyday objects, training specific to goal
  - Cognitive strategies favored
    - Van Vliet PM, et al., 2001

Most Recent

- Comparing MRP versus Bobath for prevention of post-stroke apathy
  - Large RCT
  - Significantly less apathy severity in participants receiving MRP compared with Bobath at each time point
  - Those receiving Bobath were 1.629 times more likely to develop poststroke apathy over 12 months
    - Chen L et al, J Stroke Cerebrovasc Dis, 2019

More current treatment approaches based on motor learning:

- Don't really have a catchy name or abbreviation…
  - Specific skills training
  - Task specific training
  - Intensive mobility training
  - Repetitive task-specific practice

Motor Learning and Neuroplasticity…

What's the Connection?

Learning Dependent Plasticity

- Animal model examples and human subjects examples
- Task specific motor learning important stimulant for neuroplastic change and remediation of maladaptive patterns post stroke
  - Boyd, Vidoni, Wessel, 2010
- Brain continuously remodels to encode new experiences and cause behavior change
  - Kleim JA, Jones TA, 2008
- Bottom line: skill learning leads to rewiring of motor cortex
  - Kleim JA, 2011

Motor Learning and Recovery of Function

- Learning is our best hope for brain remodeling
- Learning causes reorganization
- Brain injury changes how the brain responds to learning
    - Kleim JA, Jones TA, 2008
- Impaired learning after multiple concussions and decreased synaptic plasticity related
    - De Beaumont et al, 2011

Recovery is a Relearning Process

- Functional improvement is a relearning process
- Brain relies on same neurobiological processes it used to acquire skill initially
    - Kleim JA, 2011
- Motor learning, not motor activity, leads to increased numbers of synapses in motor cortex
    - Kleim JA et al, 1996

Activity Dependent Plasticity

- Task Complexity
- Task Difficulty/Intensity
- Task Specificity
- Sensory Experience
  - Fisher BE, Sullivan KJ, Top Stroke Rehabil, 2001.

So…

Are you promoting or preventing motor learning?

Principles of Motor Learning

The "Familiar" Factors in Motor Learning

- Practice Levels
  - "Most important factor in retraining motor skills is amount of practice"
- Feedback
  - Intrinsic
  - Extrinsic
    - Knowledge of Results (versus Knowledge of Performance)

Shumway-Cook A, Woollacott MH, Motor Control – Translating Research into Clinical Practice, 2017

Practice

- Performance improvement is dependent upon amount of practice
  - Schmidt & Lee, 1999
- But there are other factors in addition to the amount of practice

Amount of Practice

- Large number of trials:
  - More opportunities to establish relationships among various types of info associated with each movement
    - Enhance stability of recall and recognition schemas
  - Requires more instances of retrieval of motor programs
    - May help automatize activation of generalized motor patterns for future use

Am J Speech Lang Path. 2008; 17: 277-98

Variability of Practice

- Variable practice relies on higher order motor areas, while constant practice depends more heavily on primary motor cortex for motor-memory consolidation
  - Kantak et al, 2010
- May work best when variability is within same generalized motor pattern
  - Hall & Magill, 1995
- May not be applicable for everyone
  - Dick et al, 2000

Practice Conditions

- Massed v Distributed Practice
- Constant v Variable Practice
- Random v Blocked Practice
- Whole v Part training
- Transfer
- Mental Practice
- Guidance v Discovery Learning
  - Shumway-Cook A, Woollacott MH, Motor Control – Translating Research into Clinical Practice, 2017.

Practice Conditions

- Massed v Distributed
  - Massed = amount of practice time in trial > amount of rest between trials
  - Distributed = amount of rest between trials ≥ amount of time for trial
  - In continuous tasks, massed practice decreases performance (fatigue), not much affect on learning
  - In discrete tasks, evidence not clear
- Constant v Variable
  - Variable practice increases ability to adapt and generalize
  - Most useful when learning tasks performed in variable conditions

Practice Conditions

- Random v Blocked
  - Blocked = better performance
  - Random = better retention and transfer
  - Contextual interference: increased difficulty initially make learning more effective
  - Random may be inappropriate until earner understands dynamics of task
- Whole v Part
  - Interim steps via task analysis
  - Practice parts before combining into whole
  - Takes things out of context
  - Quick, discrete skills and continuous skills should be practiced as whole
  - Serial skills are ok to do part-whole
  - Bottom line, have to get to the WHOLE practice sooner rather than later

Practice Conditions

- Transfer
  - A task learned in one condition transfers to another
  - Depends on similarity between tasks or environments
- Mental Practice
  - A cognitive rehearsal
  - Enhance learning when physical practice not possible
  - Has been shown to significantly increase efficacy of repetitive task-specific practice
    - Hewett et al, 2007; Page et al, 2007; Riccio et al, 2010; Liu et al, 2004
  - Retention of motor improvements have been demonstrated to last at least 3 months in patients with stroke
    - Page S et al, 2011

The power of observation

- Viable method of practicing complex motor skills
  - More to see and be extracted from observation of complex task
  - Offers opportunity to engage in processing that could not occur in early practice
  - Providing observational practice during rest intervals increases training efficiency
    - Wulf G, Shea CH, Psychonomic Bull Rev, 2002.
- Observation of other learners performing increases training efficiency
  - Shea CH et al, J Motor Behav, 2000; Shea Ch, et al, J Motor Behav, 1999.

Combining Action Observation and Motor Imagery

- Motor imagery: cognitive process in which subject imagines performance of movement without action
- Action observation: observation of actions performed by others
- BOTH **activate same neural structures** responsible for actual execution the action
- Evidence that concurrent AO+MI:
  - Elicits increased activity in motor regions
  - More direct impact on motor outcomes
    - Eaves DL, Riach M, Holmes PS, Wright DJ, *Front Neurosci*, 2016.

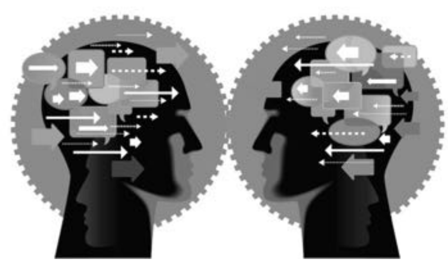
AO + MI Example

- Effect on balance training
- 3 groups of participants (healthy)
  - MI (imagined postural exercises)
  - AO+MI (observed videos of performance of postural exercises AND imagined being person in video)
  - CON (non-active control)
- Stand without perturbation and during perturbed stance
- Post exam: significantly decreased postural sway in both active groups

Practice Conditions

- Guidance v Discovery Learning
  - We often use guidance in neuro rehab
  - Unguided conditions less effective during acquisition, but more effective for retention and transfer
  - Replace with discovery learning – patient allowed to explore "perceptual motor workspace"
  - Trial and error discovery of best strategies and perceptual cues

Feedback



Guidance Hypothesis

- Information provided via feedback guides learner to correct movement, improving performance during practice; frequent feedback has negative effect

  Salmoni et al, 1984
- Schmidt, 1991 predicts that properties of augmented feedback are beneficial for motor learning when used to reduced error, but detrimental when relied upon

Manual Guidance vs Knowledge of Results

- Normal subjects learning a 70:30 ratio of weightbearing with standing
- 10 blocks of 12 trial practice
- 4 groups
  - 100% guidance (GD)
  - 33% guidance
  - 100% KR
  - 33% KR

Manual Guidance vs Knowledge of Results

- In practice:
  - 100% GD subjects had fewest errors
  - KR 100% second fewest
  - GD 33%, 3rd
  - KR 33% had most errors
- In learning (10 min to 1 wk retention):
  - KR 33% had fewest errors
  - 100% GD had most errors

    Sidaway B, JNPT, 2008

Feedback

- Intrinsic
  - Comes via sensory systems
  - Vision, somatosensation
  - Is movement accurate/meeting goal?
- Extrinsic
  - Augmented feedback
  - What we provide that supplements intrinsic

Augmented Feedback

- Concurrent
- Immediate
- Verbal
- Accumulated
- Knowledge of results (KR)
- Terminal
- Delayed
- Nonverbal
- Distinct
- Knowledge of performance (KP)

Schmidt and Lee, Motor control and learning. A behavioral Emphasis, 2011

More on Feedback

- Cues vs. Instructions:

- Individualized feedback not completely necessary
  - Observers performed as well as models, despite lack of individualized feedback
  - Greatest success by group that received both treatments
    - Hebert EP, Landin D, 1994

Augmented Feedback

- Scheduling Feedback
  - Frequency – How would you rate yours currently
  - Summary KR: KR at end of block of practice
  - Fading: giving KR early in practice (50% frequency) and gradually reducing later in practice
  - Number of trials before KR: depends on complexity of task; 5-15 trial in literature
  - Reduced frequency supported in speech motor learning as well
- Delayed KR is best:
  - Example:
    Movement →delay →KR → post KR delay →Movement
  - Also supported in the limited speech literature

The power of feedback

- What is the impact of your feedback?
- Are you intentional with your feedback?
- Effect of erroneous KR
  - Learning incorrectly
  - Unlearning what has already been learned!

Modeling

- Visual Modeling:
  - Baby copies mother's expressions hours after birth
- Too much feedback suppresses error detection; modeling does not do that
- Movement observation, immediately following practice increases cortical excitability and enhances motor memory consolidation
  - Zhang et al, 2011

Modeling

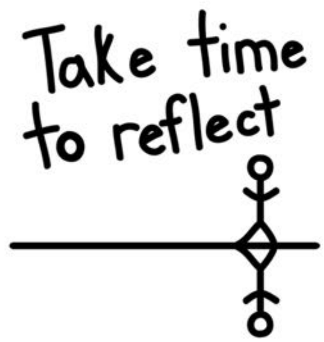
- Modeling Effects on Acquisition and Retention of golf skill:
  - 4 groups:
    - 100% modeling
    - 20% modeling
    - 10% modeling
    - control group
- 100% modeling group had best retention

  (sig different from other groups)
- This trend continued in a transference task

  (no modeling)

I will ask again…

Are you promoting or preventing motor learning?



Extrinsic Feedback after Stroke

- Review of research specific to how extrinsic feedback impacts motor learning after stroke
- Balance performance can improve from receiving visual feedback
- Auditory feedback of force production improves sit<>stand
- Providing feedback on less that 100% of trials, giving summary or average feedback enhances learning
- Instructions/feedback inducing external focus may be more effective than those with internal focus

Van Vliet PM, Wulf G. Disabil Rehabil, 2006

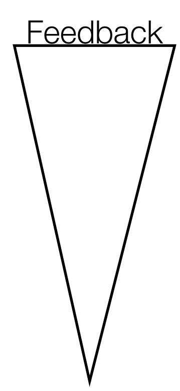
The Challenge Point

- Challenge Point Framework: model used to promote motor learning through manipulation of conditions of practice to modify task difficulty
- Used a case series of persons with stroke in training stepping reactions for improved balance
- Resulted in improved community-level walking balance, retained benefits <u>1 year later</u>
- Balance related self-efficacy and movement kinematics also improved

Pollock, CL, Boyd LA, Hunt MA, Garland J. Phys Ther, 2014

What this looked like

- Blocked practice of multidirectional stepping reactions
- Random practice of multidirectional stepping reactions
- Forward and backward stepping reactions with increased cognitive load



Pollock, CL, Boyd LA, Hunt MA, Garland J. Phys Ther, 2014

Putting this into practice…

- You have a patient s/p 2 weeks C8 SCI (complete). She has just transferred to inpatient rehab and you just initiated transfer training. Upon exam, she required Mod Assist with level surface transfers and Max to Dependent Assist with unlevel.
  - What would likely be best practice structure at this point?
  - What type of practice would most enhance motor learning?
  - How might you help her develop intrinsic feedback, as opposed to relying on extrinsic?

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Putting this into practice…

- A young athlete is working to retrain his pitching post shoulder injury. Prior to injury, he was able to throw a variety of pitches successfully (fastballs, breaking balls, and changeups). In order to successfully re-train (re-learn) pitching:
  - How might the PT structure practice to maximize motor learning?
  - When/how should PT provide feedback?

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Up Next…
Expanding the definition of motor learning

- Not **just** acquisition of movement or movement pattern
- Includes the following:
  - Cognitive processes
  - Affective reactions
  - Attentional focus
- Collaborating to meet task demands
  - Lewthwaite R, Wulf G, *Q J Exp Psychol*, 2010

Questions?

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