The Motivational and Meta-Cognitive Subsystems

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Outline

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    1. Introduction
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        2. High-level Primary Drives
        3. Drive Strength Considerations
    3. Goal Structure
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2. Meta-Cognitive Subsystem
    1. Introduction
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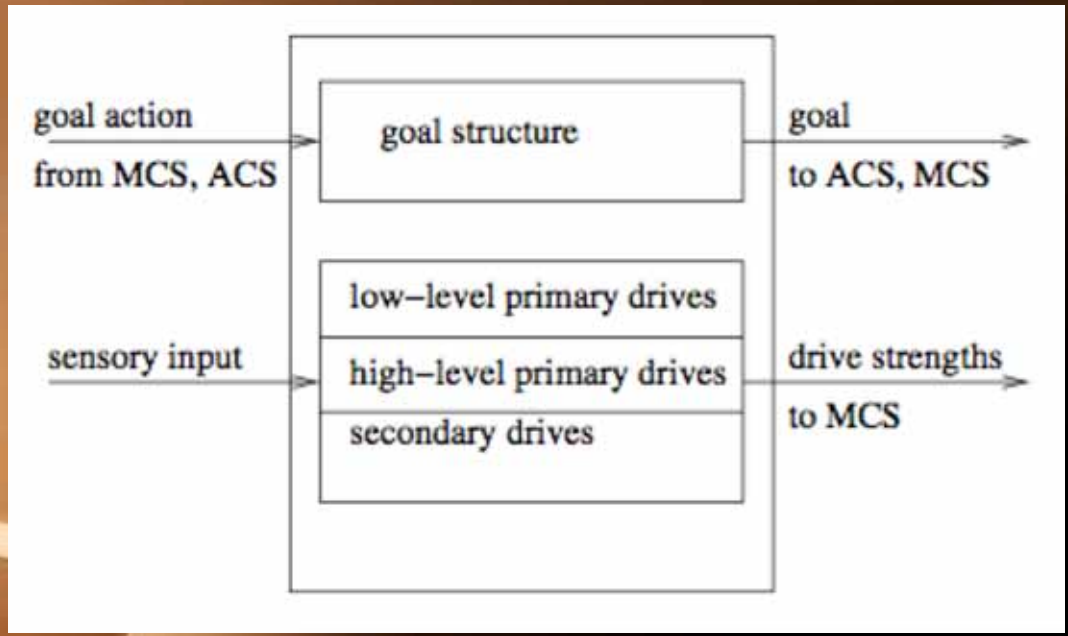
3. Simulation Examples
4. Summary

The Motivational Subsystem (MS)



Introduction

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Introduction

- A cognitive agent must address the following in its everyday activities:
  - Sustainability
  - Purposefulness
  - Focus
  - Adaptivity

Introduction

- Sustainability
  - An agent must attend to its essential needs (Toates 1986), for example:
    - Hunger
    - Thirst
    - avoiding physical dangers
- Purposefulness
  - Actions must be chosen in accordance with some criteria, instead of completely randomly (Hull 1943, Anderson 1993)
  - For the sake of enhancing sustainability of an agent (Toates 1986)

Introduction

- Focus
  - An agent must be able to direct its activities with respect to specific purposes (Toates 1987)
  - Actions need to be:
    - Consistent
    - Persistent
    - Contiguous
  - Must also be able to give up activities when necessary (Simon 1967, Sloman 1986)

Introduction

- Adaptivity
  - Must be able to change behavior (i.e. learn) for the sake of sustainability, purposefulness and focus.

Introduction

- Implicit vs. explicit representation of motivational constructs:
  - Implicit: Drives
    - The internal process of generating drives, needs or desires are not readily accessible cognitively
  - Explicit: Goal Structure
    - Explicit motivational representation consists mainly of explicit goals (Anderson & Lebiere 1998)

Introduction

- Motivational processes are highly complex and varied (Weiner 1992)
  - Cannot be captured with simple explicit goal representations alone
  - Motivational processes may be based on unconscious “needs” (cf. e.g. Maslow 1943, Murray 1938)
- Explicit goal representations arise to clarify and supplement implicit motivational dynamics

Introduction

- Reasonable to assume (Sun 2002):
  - Dual representation is applicable
  - Implicit motivational processes are primary and more essential than explicit processes
    - Basic drives
    - Basic needs
    - Basic desires
    - Intrinsic motives

Drives

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Drives*

- Hull (1950) developed the most detailed conception of “drives”:
  - *A pre-conceptual representation of motives.*
- Stricter notion of drives:
  - Physiological deficits that require reduction by corresponding behaviors (Hull 1951, Weiner 1982)
- Generalized interpretation of drives:
  - Internally felt needs of all kinds that likely may lead to corresponding behaviors
  - Physiological or otherwise
  - For end-states or process-states
  - May or may not be reduced by corresponding behavior

Drives*

- Generalized notion transcends controversies surrounding the stricter notions of drive
- Accounts for behaviors that satisfy the previously mentioned considerations

Drives

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Drives

- Low-level Primary Drives
  - Mostly physiological, evolutionarily formed, hard-wired
  - Consists of:
    - Food
    - Water
    - Sleep
    - Avoiding physical dangers
    - Reproduction
    - Etc.

Drives

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Drives

- High-level Primary Drives
  - Mostly social
  - More or less hard-wired, innate, but not physiological
  - See Sun tutorial addendum (2007) for justification

Drives

- High-level Primary Drives
- Posit the following drives (Murray 1938, Reiss 2004, Maslow 1987, James 1890):
  - Affiliation and Belongingness:
    - The drive to associate with other individuals and to be part of social entities
  - Dominance and Power:
    - The drive to have power over other individuals or groups
  - Recognition and Achievement:
    - The drive to excel and be viewed as being accomplished at a task

Drives

- High-level Primary Drives (cont.)
  - Autonomy
  - Deference
  - Similance
  - Fairness
  - Honor
  - Nurturance
  - Conservation
  - Curiosity

Drives

- Primary Drive Considerations
  - Empirical data suggests that aforementioned drives are largely uncorrelated
  - Each drive may be weighted somewhat differently
    - Leading to individual differences
  - Drives seek for a “moderate mean” (Aristotle 1953, Reiss 2004)
    - Desirable level of satisfaction
    - Neither the highest nor the lowest

Drives

- Derived Drives:
  - Secondary and more changeable
  - Acquired in the process of satisfying primary drives
  - Include:
    - Gradually acquired drives
      - Through conditioning (Hull 1951)
    - Externally set drives
      - Through externally given instructions

Drives

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Drives

- Drive Strength Considerations (Tyrell 1993)
  - *Proportional Activation:*
    - Drive activation should be proportional to perceived offset (deficit)
  - *Opportunism:*
    - Opportunities need to be incorporated when calculating desirability of alternatives in choosing actions
  - *Contiguity of Actions:*
    - Tendency to continue to the current action sequence

Drives

- *Drive Strength Considerations (cont.)*
  - Persistence:
    - Actions to satisfy a drive should persist beyond minimum satisfaction
  - *Interruption when Necessary:*
    - When a much more urgent drive arises, actions for a lower-priority drive may be interrupted
  - *Combination of Preferences:*
    - A compromise candidate may be generated that is the best in terms of the combined preferences of the different drives

Drives

- General structure of a drive:

$$ds_d = \alpha_d Stimulus_d \times Deficit_d + \beta_d$$

Where α_d is the gain and β_d is the drive baseline

- Alternatively:

$$ds_d = \alpha_d Max(\beta_d \times Deficit_d, Stimulus_d \times Deficit_d)$$

Drives*

- A few examples of calculating drive strengths:
  - Food:

$$ds_{food} = 0.95 \times Max(0.30 \times Deficit_{food}, Stimulus_{food} \times Deficit_{food})$$

  - Avoiding Physical Dangers:

$$ds_{danger} = 0.98 \times Stimulus_{danger} \times Certainty_{danger}$$

Certainty$_{danger}$ substitutes *Deficit*, but is mathematically equivalent

  - Affiliation and Belongingness:

$$ds_{a\&b} = 0.50 \times Deficit_{a\&b} \times Stimulus_{a\&b} + 0.20$$

  - Recognition and Achievement:

$$ds_{r\&a} = 0.40 \times Deficit_{r\&a} \times Stimulus_{r\&a} + 0.10$$

Drives*

- *Deficit*$_d$ can represent a physiological deficiency or an innate sensitivity toward certain inclinations
- *Stimulus*$_d$ may consist of:
  - Sensory information
  - Working memory items
  - Current goal
  - A meta-cognitive subsystem filtered interpretation of the above (will be discussed later)

Drives

Questions?

Goal Structure

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Goal Structure

- More unique, more specific, more explicit than drives
- Drives provide the context within which explicit goals are set
- Goals are different from drives in many respects:
  - Multiple drives activated at the same time vs. only one goal being pursued at a time
  - Drives are defused in focus whereas goals are often more specific (McFarland 1989, Anderson and Lebiere 1998)
  - Drives are more implicit, while goals are more explicit (Murray 1938, Maslow 1943, Hull 1951)
  - Drives are more hardwired, whereas goals are more flexibly formed and carried out (Hull 1951, Sun 2003)

Goal Structure

- Goals provide specific, tangible motivations for the actions chosen and performed in the ACS
- Recall, actions chosen in the ACS are the result of current state and current goal considerations
- The goal structure provides a framework for communicating motivation to the other subsystems
- Implemented in CLARION as either:
  - A goal list
  - A goal stack

Goal Structure

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Goal Structure

- Goal List
  - Realistic approach toward cognitive modeling of motivational processes
  - Randomly accessible linear structure that contains a set of goal items
    - Each slot of the list can contain a goal chunk
      - Goal chunks are made up of:
        - A goal dimension
        - A number of parameter dimensions
    - Location of goal items on the list is irrelevant
  - Goal items on the goal list compete with each other to become active (using Boltzmann distribution)

Goal Structure

- Goal List (cont.)
  - Goal items have a recency based base-level activation that allows goals to slowly decay over time:

$$B_i^g = iB_i^g + c \times \sum_{l=1}^{n} t_l^{-d}$$

Where t_l is the *lth* setting of goal *i* and iB_i is the initial value.

  - Goals compete using BLA through a Boltzmann distribution

Goal Structure

- Goal List (cont.)
  - Can be used to generate behavioral “routines”
    - By approximating stack-like behaviors using BLA and moment-to-moment state information
  - List can handle complex or subtle situations
  - Goal alternation is possible using a goal list (unlike a goal stack)

Goal Structure*

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Goal Structure*

- Goal Stack
  - Linear structure of multiple items in which only the top item may be accessed
    - Only one goal item may be active at a time
  - Items may be added to or removed from the top of the stack
  - A currently active goal becomes inactive when a new goal is added on top of it
    - Becomes reactivated when all goals on top of it are removed

Goal Structure*

- Goal Stack (cont.)
  - Goal stack actions:
    - *Push i {dim,value}*
      - *i* is the value of the goal symbol for the goal dimension, *{dim,value}* are optional parameters to be set along with the goal
    - *Pop*
    - *Do-nothing*

Goal Structure*

- Goal Stack (cont.)
  - Allows for the emergence and application of relatively fixed patterns of behavior (routines)
  - Problems:
    - Too idealistic for modeling cognitive processes realistically
    - Much of the subtlety and complexity involving goal coordination is lost
    - Rough approximation and abstraction of a complex motivational and meta-cognitive process

Goal Structure

Questions?

Meta-Cognitive Subsystem

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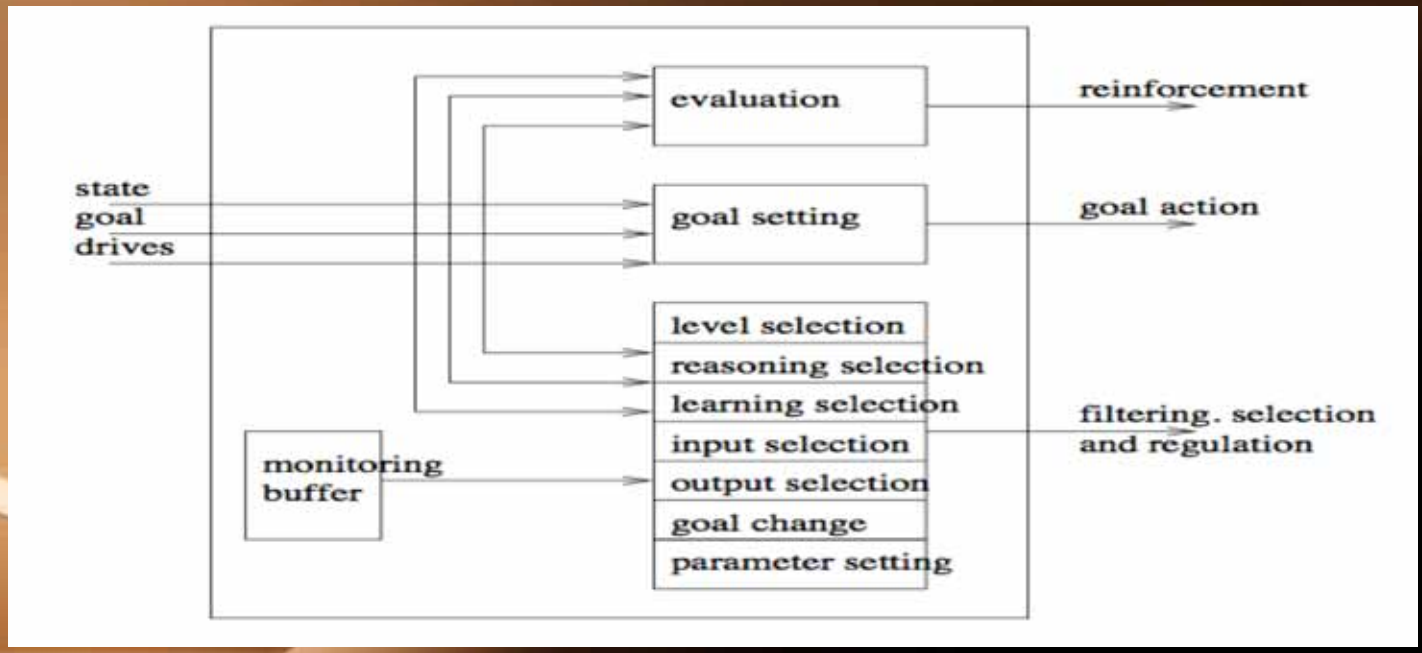
The Meta-Cognitive Subsystem (MCS)



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Introduction

- Meta-cognition refers to (Flavell 1976):
  - *One's knowledge concerning one's own cognitive processes and products*
  - *The active monitoring and consequent regulation and orchestration of processes in relation to the cognitive objects or data on which they bear*
    - Usually in the service of some concrete goal or objective
- Drive strengths and goal structures in the MS lead to the need for meta-cognitive control
  - Regulates:
    - Goal structure
    - Other cognitive processes

Introduction

- Like the ACS, the MCS is:
  - Action-centered
  - Comprised of two levels:
    - Bottom level is made of implicit decision networks (IDNs)
    - Top level consists of groups of rules
- *Mostly the bottom level takes effective control
  - Meta-cognitive control is, usually, fast and effortless (Reder and Schunn 1996)
  - Under some circumstances the top level can also exert influence (Forrest-Pressley and Waller 1984)

Structure & Responsibilities

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Structure & Responsibilities*

- Several types of meta-cognitive processes are available:
  - Behavioral aims
    - Goal setting
    - Reinforcement setting
  - Information filtering
    - Focusing of inputs to the various other subsystems
  - Information acquisition
    - Selection of learning methods
  - Monitoring buffer
    - Monitors performance of the various subsystems

Structure & Responsibilities*

- Available meta-cognitive process types (cont.):
  - Information utilization
    - Setting of reasoning methods
  - Outcome selection
    - Selection of outcome
  - Cognitive modes
    - Level selection/integration
  - ACS/NACS parameter setting

Structure & Responsibilities

- Divided into a number of modules:
  - Goal-setting
  - Reinforcement
  - Filtering
  - Learning & Reasoning
  - Level selection
  - Parameter setting
  - Monitoring buffer
    - ACS performance & learning
    - NACS performance & learning
  - And others

Structure & Responsibilities

- Goal-setting
  - The actual process of goal setting is performed by the MCS
  - Maps the strengths of all the drives and the current state (and possibly other factors) to the current goal to be set
  - *Two goal setting methods:
    - Balance-of-interests (preferred):
      - Each drive votes for multiple goals
      - Goal with the highest score becomes the new goal
        - Bonus is given to current goal (to prevent flipping and promote drive persistence)
    - Winner-take-all:
      - Drive with the highest strength wins
      - New goal is the goal that best attends to the winning drive

Structure & Responsibilities*

- Goal-setting (cont.)
  - General formula for setting goals:

$$Act_g = \sum_{d=1}^{n} Relevance_{d \rightarrow g} \times ds_d$$

Where $Relevance_{d \rightarrow g}$ is a measure of how well the goal (historically) addresses the drive

  - $Relevance_{d \rightarrow g}$ might be calculated using a method similar to information gain in the top level of the ACS

Structure & Responsibilities

- Reinforcement
  - MCS can address the main issue surrounding reinforcement learning:
    - How to come up with an appropriate reinforcement signal
  - The real world does not provide a simple, scalar reinforcement signal
    - Instead simply changes into a “new state” after an action is performed
    - An appropriate reinforcement signal has to be determined “internally” by synthesizing various information

Structure & Responsibilities

- Reinforcement (cont.)
  - Reinforcement generation can be handled by a module that:
    - Evaluates the current state in terms of the current goal, in the context of the currently active drives, and determines:
      - If the goal is satisfied or not (binary reinforcement)
      - By how much the current state satisfies the goal (graded reinforcement)
    - Takes external and internal sensory information, drives, and the goal (and possibly other factors) as input
  - Minimally necessary to produce an evaluation for states that directly satisfy a goal in some way
    - Sequential decision learning (such as Q-learning) can automatically propagate reinforcement to temporally adjacent states and actions

Structure & Responsibilities*

- Reinforcement (cont.)
  - Can be accomplished either implicitly, explicitly, or both
    - Implicitly:
      - A neural network generates reinforcement signals from the current state
    - Explicitly:
      - A reinforcement function is specified explicitly via a set of simple rules
      - Mapping from certain states to reinforcement signals

Structure & Responsibilities*

- Filtering
  - Attention focusing of input and output is based on:
    - Current sensory input
    - The current goal
    - Drives
    - Working memory
    - The performance of the subsystems
      - As determined by the monitoring buffer
  - Allows dimensions to be either suppressed or enhanced before being delivered to a subsystem
    - Different subsystems can get different subsets of the total information available
    - Allows different subsystems to have different focuses

Structure & Responsibilities

- Learning & Reasoning
  - Learning & reasoning methods in the ACS & NACS may be selected by the MCS
  - The learning & reasoning methods can be set separately within each subsystem and for different modules within each subsystem

Structure & Responsibilities

- Level Selection
  - Can use current state, goal, and drive information to determine in which level of the ACS action recommendations are made.
  - One possible method for level selection may be determined by drive strengths using a “catastrophe curve” (Hardy & Parfitt 1991)
    - Essentially an inverted u-curve that follows approximately a parabolic trajectory:

$$P_{BL} = ax^2 + bx + c$$

Where x is some combination of drive strengths (possibly average or max), a < 0, and 0<c<1

Structure & Responsibilities

- Parameter Setting
  - Includes:
    - Bottom-level learning rate
    - Q-learning discount factor for bottom-level learning
    - Temperature in stochastic selection
    - Rule learning thresholds
    - Specialization and generalization thresholds
    - Various other parameters in the NACS

Structure & Responsibilities

- Monitoring Buffer
  - Stores various information about the internal state of the system
  - Contains information about:
    - Current state information
    - Current goal information
    - Performance statistics about the ACS and NACS modules
    - Parameters that can be manipulated by the MCS

Structure & Responsibilities

Questions?

Simulation Examples

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Simulation Examples

- Lack of knowledge inference task (Sun, Zhang & Matthews 2006)
  - Deals with protocols that indicate meta-cognitive reasoning:
    - Protocol Examples:

      Q: Have you ever shaken hands with Richard Nixon?

      A: No…How do I know? It's not something that one would forget…(Gentner & Collins 1991)

      Q: Is the Nile longer than the Mekong river?

      A: I think so… Because in junior high, I read a book on river,… the Amazon was in there and the Nile was in therre and they were big and long and important… (Collins 1978)

      Q: Is Kissinger 6'6" tall?

      A: If Kissinger were 6'6" tall, I would know he is very tall. I don't so he must not be that tall. (Collins 1978)

Simulation Examples

- Lack of Knowledge inference task (cont.)
  - Inferences were made based on:
    - The lack of knowledge about something
    - The importance/significance of that knowledge
  - To make these inferences, MCS must:
    - Monitor the reasoning process
    - Intervene and redirect the reasoning process

Simulation Examples

- Setup
  - Intended to capture both meta-cognitive monitoring and intervention
  - Subsystems used:
    - ACS
      - Directed reasoning of the NACS
    - NACS
      - Performed inferences
    - MCS
      - Selected information to be used and reasoning methods to be applied
      - Monitored the progress of inference in the NACS
      - Performed intervention by starting “lack of knowledge” inference in NACS

Simulation Examples

- Setup (cont.)
  - ACS used mainly top-level rules for directing NACS reasoning

If $goal = regular\_inference$, then perform one-step of inference in the NACS

If $goal = regular\_inference$ & chunk i is a conclusion chunk with $S_i^c > threshold_s$ and $\forall j : S_i^c > S_j^c$, then retrieve chunk i

If $goal = LOK\_inference$ & no conclusion chunk has $S_i^c > threshold_s$ but there are many associative rules pointing to the conclusion chunk, then the conclusion is negative

If $goal = LOK\_inference$ & no conclusion chunk has $S_i^c > threshold_s$ & there are no associative rules pointing to the conclusion chunk, then the conclusion is indeterminate

$threshold_s$ set to $.1$

Simulation Examples

- Setup (cont.)
  - NACS top level had associative rules of the following form:

$$River_a \rightarrow long\_river$$
$$River_b \rightarrow long\_river$$
$$River_c \rightarrow long\_river$$

  - NACS bottom level was trained with the same knowledge as the associative rules

Simulation Examples

- Setup (cont.)
  - MCS
    - Goal-setting
      - Began by setting goal as "*regular_inference*"
      - Chose "*LOK_inference*" in the goal-list when the "lack-of-knowledge" condition was detected
        - Detected by uniformly low activation in the NACS performance section of the MCS monitoring buffer
    - Filtering
      - Selected relevant input dimensions to be used by the NACS
    - Reasoning
      - Selected "*forward chaining with SBR*" reasoning method in the NACS

Simulation Examples

- Results
  - Captured “lack-of-knowledge” inference exhibited by the human subjects in the protocols described earlier
  - As predicted
    - When a simulated subject had a (relatively) large amount of knowledge about a conclusion but could not reach that conclusion in a particular instance, then a lack-of-knowledge inference was initiated and a negative answer was produced
    - When a simulated subject had little knowledge about a conclusion, then a lack-of-knowledge inference was not used and no conclusion was given

Simulation Examples

Questions?

Simulation Examples

- Stereotyping task (Lambert et al 2003)
  - Two groups
    - Private
    - Anticipated Public
  - Primes
    - 4 black faces (2 male, 2 female)
    - 4 white faces (2 male, 2 female)
  - Targets
    - 4 guns
    - 4 tools (2 wrenches, 1 drill, 1 ratchet)

Simulation Examples

- Cognitive Control Estimate
  - Calculated approximate frequency of controlled responses

$$CCE = P(correct \mid congruent) - P(stereotypic\_error \mid incongruent)$$

- Accessibility Bias Estimate
  - Calculated likelihood of making stereotyped response when control failed

$$ABE = \frac{P(stereotypic\_error \mid incongruent)}{(1-c)}$$

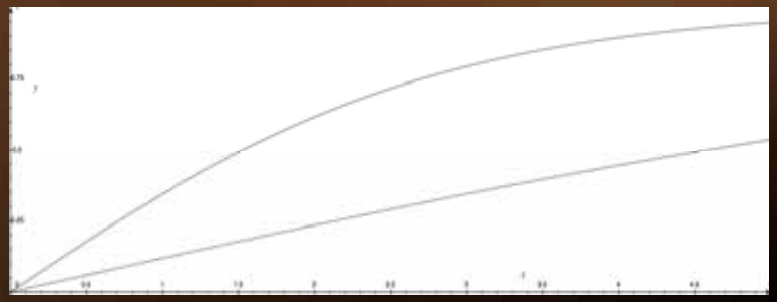
Simulation Examples

- Setup
  - The MS - honor drive
    - Inputs:
      1. Deficits: reflecting individual differences (trait anxiety)
      2. Situational stimulus (capturing group condition difference)
  - The MCS - level integration - inverted u-curve
    - Input: drive strength
    - Output: P_{TL} (cognitive control estimate)
  - The ACS
    - Top Level:
      - 8 Fixed Rules - maps target features to object type
        - Identifications of targets obtained during practice trials
    - Bottom Level:
      - Neural Network (25 input, 5 hidden, 2 output)
        - Maps characteristics of target and prime to object type
        - Pre-trained to map race to object type based on accessibility bias estimate

Simulation Examples

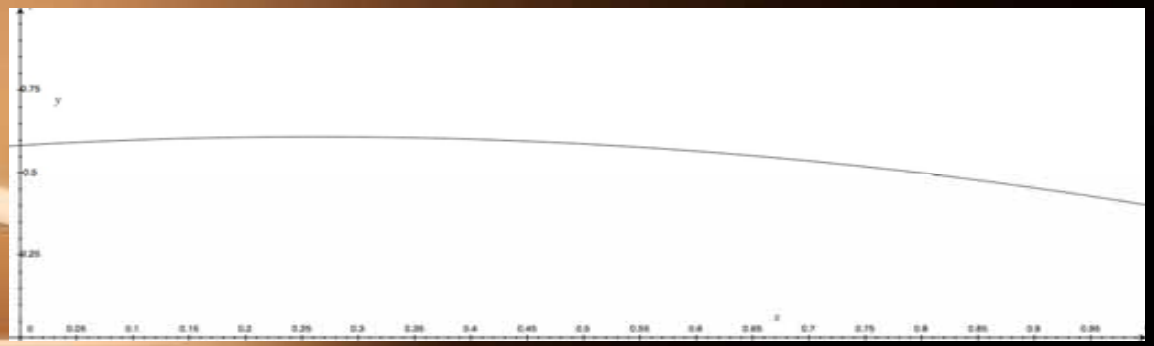
- Setup (cont.)
  - The MS:

$$ds_{honor} = \tanh(stimulus_{honor} \times deficit_{honor})$$



  - The MCS:

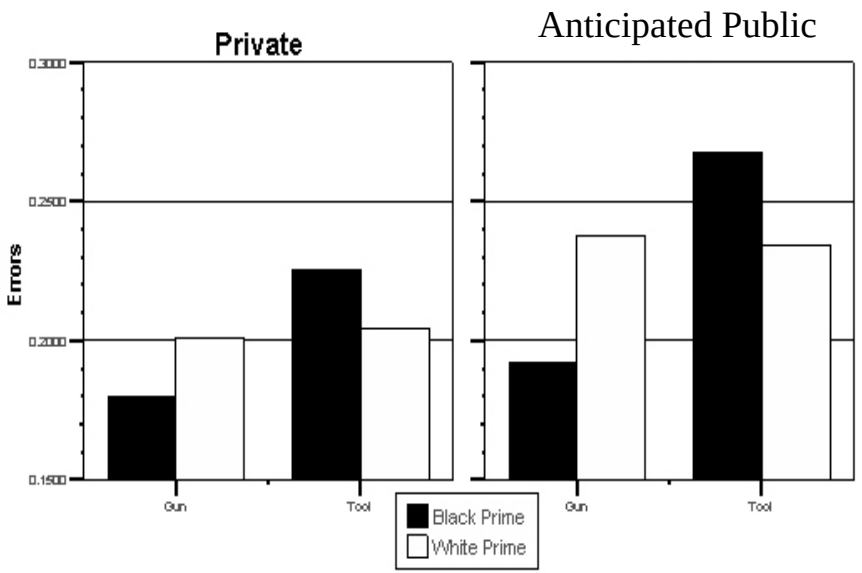
$$P_{TL} = -0.38x^2 + 0.20x + 0.58$$



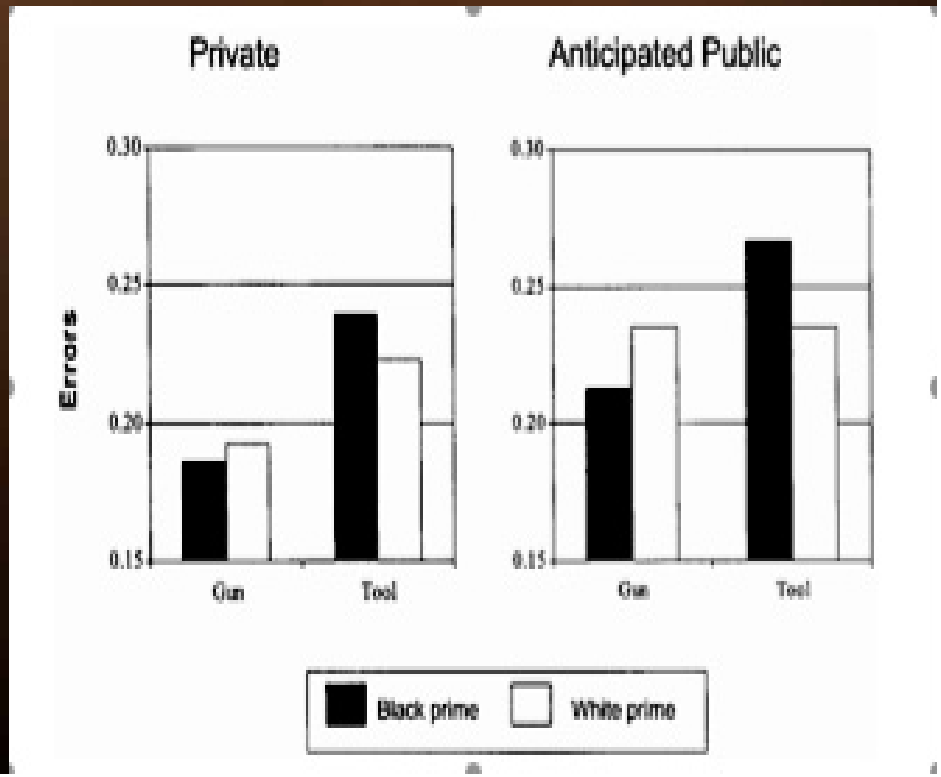
Simulation Examples

- Results

Simulation Results



Lambert Results



Simulation Examples

- Results (cont.)

Lambert Cognitive Control Estimate

GROUP	Black Prime	White Prime
Private	.61	.60
Public	.53	.53

Simulation Cognitive Control Estimate

GROUP	MCS	Black Prime	White Prime
Private	.60	.60	.60
Public	.53	.52	.52

Lambert et al Accessibility Bias Estimate

GROUP	Black Prime	White Prime
Private	.56	.53
Public	.56	.49

Simulation Accessibility Bias Estimate

GROUP	ACS Black Prime	ACS White Prime	Black Prime	White Prime
Private	.57	.51	.57	.50
Public	.56	.51	.56	.51

Simulation Examples

- Results (cont.)
  - Significant prime x object interaction in both groups
  - Stronger prime x object interaction in public group than in private group
  - Main effect of object
  - Main effect of context over cognitive control estimates
  - No effect of prime over cognitive control estimates
  - Significant prime x context interaction over cognitive control estimates
  - Main effect of prime over accessibility bias estimates
  - No effect of context over accessibility bias estimates

Simulation Examples

Questions?

Summary

1. Motivational Subsystem
    1. Introduction
    2. Drives
        1. Low-level Primary Drives
        2. High-level Primary Drives
        3. Drive Strength Considerations
    3. Goal Structure
        1. Goal List
        2. Goal Stack
2. Meta-Cognitive Subsystem
    1. Introduction
    2. Structure & Responsibilities
3. Simulation Examples
4. **Summary**

Summary

- MS
  - To survive, a cognitive agent's actions must be sustainable, purposeful, focused, and adaptive
  - In CLARION, represented by drives on the bottom-level and a goal structure on the top level
  - Low-level primary drives are mostly physiological, hard-wired, and evolutionarily formed
  - High-level primary drives are more socially oriented
  - Drives seek for a "moderate mean"

Summary

- MS (cont.)
  - Drive strengths are determined based on considerations of proportional activation, opportunism, contiguity of actions, persistence, interruption when necessary, and combination of preferences
  - Goals provide specific, tangible motivations for the actions chosen and performed by the ACS
  - The goal structure provides a framework for communicating motivation to the other subsystems
  - The goal structure is implemented in CLARION using either a goal stack or a goal list

Summary

- MCS
  - Divided into modules for:
    - Goal-setting
    - Reinforcement
    - Filtering
    - Learning & Reasoning
    - Level selection
    - Parameter setting
    - Monitoring buffer

Summary

Thank You

Questions?