Next Generation Model of Perception and Action

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Talk Overview

Progress in Architectural Perceptual-Motor Systems

Plan for Talk

Progress in Architectural Perceptual-Motor Systems

A major focus of EPIC development is perceptual and motor systems.
EPIC - first modern "embodied" computational cognitive architecture.

Steady progress, but recent serious developments.
Modeling the visual system and visual search tasks - important progress.
Motor system based on "conventional wisdom" in the experimental cognitive psychology literature.
- Made data hard to fit in high-speed tasks.

Conventional wisdom turned out to be ambiguous (or wrong).
Primacy of spatial information in perceptual-motor system.

Summarize the basic approach, present results, and point to future developments of the next-generation perceptual-motor system.

My bias is towards modeling HCI tasks.
A practical domain where "natural" environment is relatively simple.

Plan for Talk

Describe key features of EPIC architecture.

Summarize why perceptual-motor constraints are critical.

Introduce visual search tasks - sample domain where visual and motor issues appear.

One specific visual search task and its model.

Reinterpretation of empirical literature on motor systems.

Pervasive spatiality in perception and action.

Description of the EPIC Architecture

Goals of EPIC Project

The EPIC Architecture

Diagram of the Current EPIC Architecture

Perceptual Processors

Motor Processors

Motor Processors (continued)

Cognitive Processor

Goals of EPIC Project

Develop a predictive and explanatory theory of human cognition and performance.

- Codify scientific knowledge.
- Elucidate executive processes.
- Explain multitask performance.

Make it accurate and practical enough to use for simulated humans in system design methodology.

- Simulate the human-machine system; iterate machine design to achieve required system performance.
- Similar to parallel-developed GOMS modeling system for HCI design.

The EPIC Architecture

Basic assumptions

Production-rule cognitive processor.
Parallel perceptual and motor processors.

Fixed architectural properties

Components, pathways, and most time parameters

Task-dependent properties

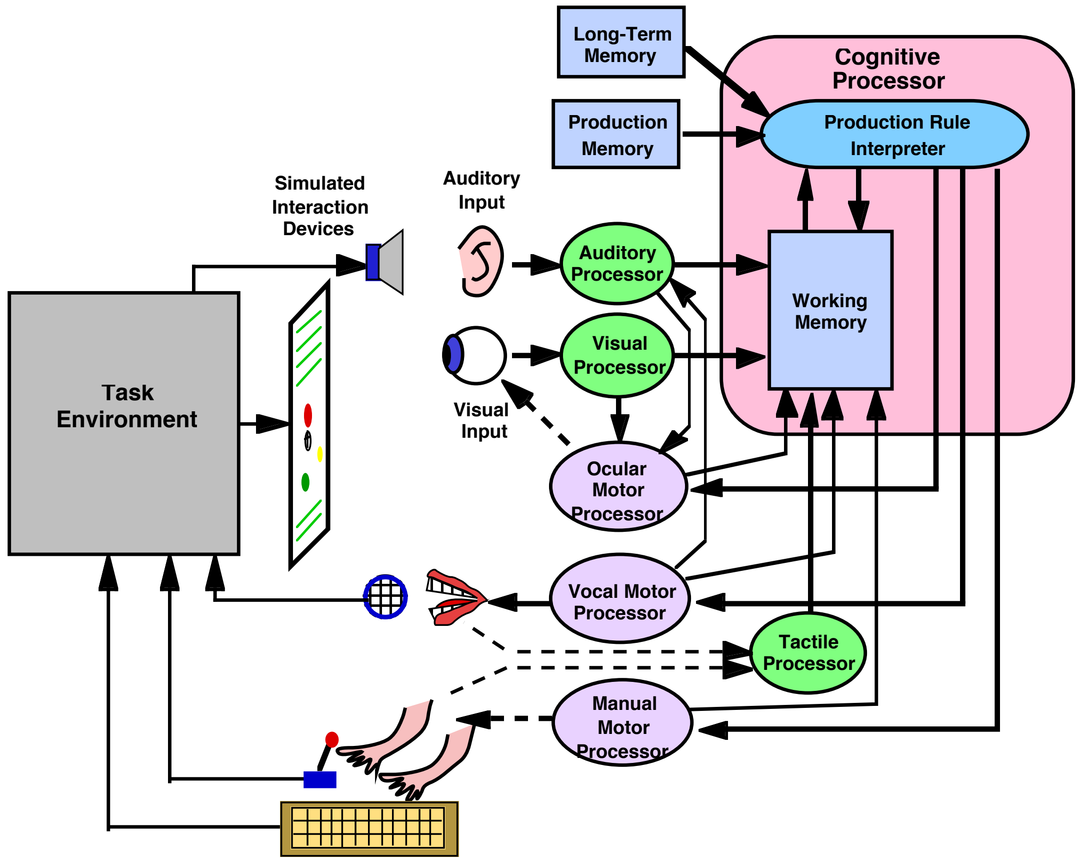
Cognitive processor production rules.
Perceptual recoding.
Response requirements and styles.

Currently, a performance modeling system.

Theory of human performance not finished - plenty of work still to be done!

See *Epic Architecture Principles of Operation* for details.

Diagram of the Current EPIC Architecture



Each box is a software module in the simulation software.

Perceptual Processors

Inputs
Symbolically-coded changes in sensory properties.

Outputs
Items in modality-specific partitions of Working Memory.

Visual

- Eye model transduces visual properties depending on retinal availability.
  Depends on distance from fovea, size, other properties.
- Visual properties take different times to transduce.
  Detection: Timing: 50 ms.
  Shape information: Timing: 100 ms, typical.
- Encodes additional perceptual properties in Visual Working Memory.
  Timing: Additional 100 ms, typical.
- Maintains internal representation of visual objects.
  Location information directly available to motor processors.
- Certain changes reported to the Ocular Motor Processor.
  Onsets, movement.

Auditory

- Important, but not elaborated here.

Motor Processors

Inputs
Symbolic instructions from the cognitive processor.

Outputs
Symbolic movement specifications and times.

Motor processing *- now questionable*
Movement instructions expanded into motor features.
- E.g., style, effector, direction, extent.

Motor movement features prepared.
- Features can be prepared in advance or re-used.
  Later execution is faster.

Movement is physically executed.

Timing:
50 ms/feature preparation. *- now questionable*
50 ms movement initiation delay.
Movement-specific execution time (e.g. Fitts' Law).

Cognitive processor informed of current state.

Motor Processors (continued)

Ocular Motor Processors (voluntary & involuntary)

Generates eye movements from commands or visual events.

- Long-loop cognitive control - voluntary processor.
  Saccades.
- Short-loop visual control - involuntary processor.
  Saccades and smooth movements.

Manual Motor Processor

Both hands are controlled by a single processor

- A fundamental limitation.

A variety of hand movement styles (more to be re-implemented)

- Pointing, button pushing, controlling.

Vocal Motor Processor

Not very elaborated at this time.

Cognitive Processor

Programmed with production rules:

Rules represent the procedural knowledge required to perform the task.
Uses the Parsimonious Production System (PPS) interpreter - very simple.

Interpreter updates working memory on each cycle, and fires all rules that match on each cycle.

Timing: 50 ms/cycle

Working Memory partitions:

Modal stores:

- Visual
  Represents current visual situation.
  Slaved to visual input.
- Auditory
  Items disappear with time.
- Motor
  States of motor processors.

Control store:

- Goal, Step, Strategy, Status items for method control and sequencing.

Tag store:

- Associates a modal working memory item with a symbol designating a role in production rules - analogous to a variable and its binding.

Amodal WM:

- Additional information whose psychological status is not yet clear.

Critical Role of Perceptual-Motor Constraints

Importance of Perceptual-Motor Constraints

Cognitive versus Perceptual-Motor Constraints

Some Important Perceptual-Motor Constraints

State of the Scientific Literature about Constraints

Brief Rant about Conventional Theoretical Wisdom

Importance of Perceptual-Motor Constraints

1990s: Embodied Cognitive Architectures
Cognitive architectures began to incorporate perceptual and motor systems and their constraints.

Earlier: Cognition was "disembodied."
Outside world directly known to cognition which directly acts on the world.
No constraints from perceptual or motor mechanisms.

Now: Cognition works through the peripheral systems, which limit what and when information is available and when actions can be taken.
Extremely powerful constraints.

In many tasks, performance is primarily limited by peripheral perceptual-motor activities rather than central cognitive limitations.
Account for many key issues in a variety of tasks.
Analogous to traditional bottlenecks in computing.

Ignoring can result in absurd models.

Can ignore only in very heavily cognitive tasks.

Cognitive versus Perceptual-Motor Constraints

What dominates a task?

Heavily cognitive tasks: Human “thinks” for most of the time.

- E.g. Online stock trading system.

But many HCI tasks are dominated by perceptual-motor activity.

A steady flow of physical interaction between human and computer.

Time required depends mainly on:

- Computer's behavior - determined by the design.
- Human perceptual-motor characteristics - many well-documented properties.

Some Important Perceptual-Motor Constraints

Visual resolution depends on eye position, specifics of visual properties.

Different eye movement types and timing.

Different hand movement types and timing.

Cross-constraints for visually-aimed movements.

Hands bottlenecked through single processor, unless two-hand movement style has been learned.

Auditory and speech input recognition timing.

Speech output timing.

Verbal working memory uses auditory and vocal processors, thereby limited by decay and production rate properties.

Visual working memory appears to have large short-term capacity, small but reliable long-term capacity under cognitive control.

State of the Scientific Literature about Constraints

Scientific psychology (“Experimental Psychology”) has been underway since 1879.

Tremendous collection of empirical data on human abilities.

However, very spotty coverage due to quirks of the research culture.

Basic research:

- Strong tendency to avoid applied issues, so mostly artificial tasks used.
- Intense "drill down" of small-scale empirical and theoretical ideas, not comprehensive theory.
- Emphasis on “odd” phenomena, rather than mainstream phenomena.
- Pursuit of qualitative phenomena and hypothesis testing, rather than determining quantitative functions and parameters of human performance.

Applied research (especially in Human Factors):

- “Putting out fires” instead of developing science base.
- Extremely specific experiments or user tests with little generalizability.
- Acceptance of “quick & dirty” rules of thumb, instead of developing theory.

For every relevant phenomenon, there is a haphazard mixture of useful results, pointless results, and missing results.

- Constraints aren't just sitting there ready to be picked up and used.

Brief Rant about Conventional Theoretical Wisdom

Conventional wisdom in experimental cognitive psychology:

Theoretical explanations for interesting phenomena that seem to work well and become generally accepted.
Basis for new experiments; empirical work interpreted in these terms.

Often misleading or even wrong because:
Based on incomplete, narrowly-focused empirical results.
Verbal theorizing, with only limited quantitative analysis.
Theoretical alternatives not seriously considered.

No substitute for quantitative computational modeling that takes task strategies and architectural constraints fully into account.

I will be making various negative remarks about conventional wisdom.

Visual Search Introduction

Task Domains of Interest are Visually Intensive

Preliminary (First Draft) MMWS Task Model Display

Why Visual Issues are Major

Need: An Accurate Visual System

Current Visual System

Sub-Need: An Accurate Model of Visual Availability

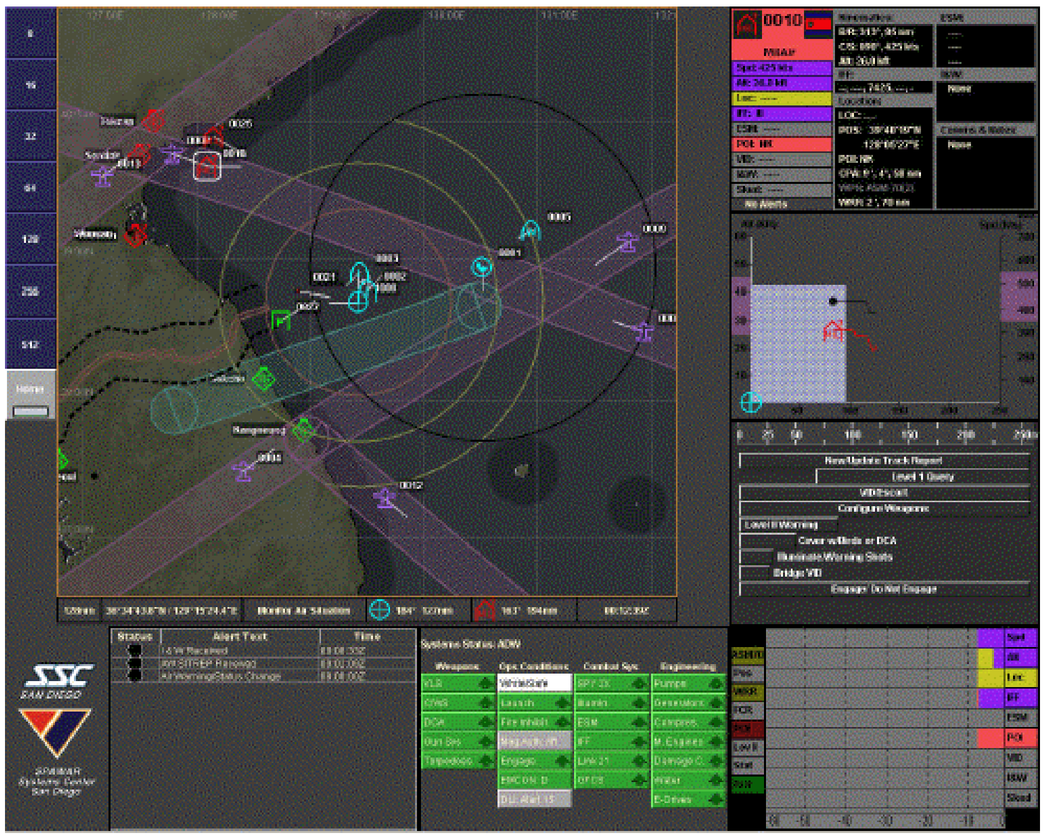
Distribution of Receptors

Example of Visual Availability Results

Visual Availability Support in EPIC

Task Domains of Interest are Visually Intensive

MultiModal WatchStation Display - actually a quiet time.
Quite a few things not directly used in the task.



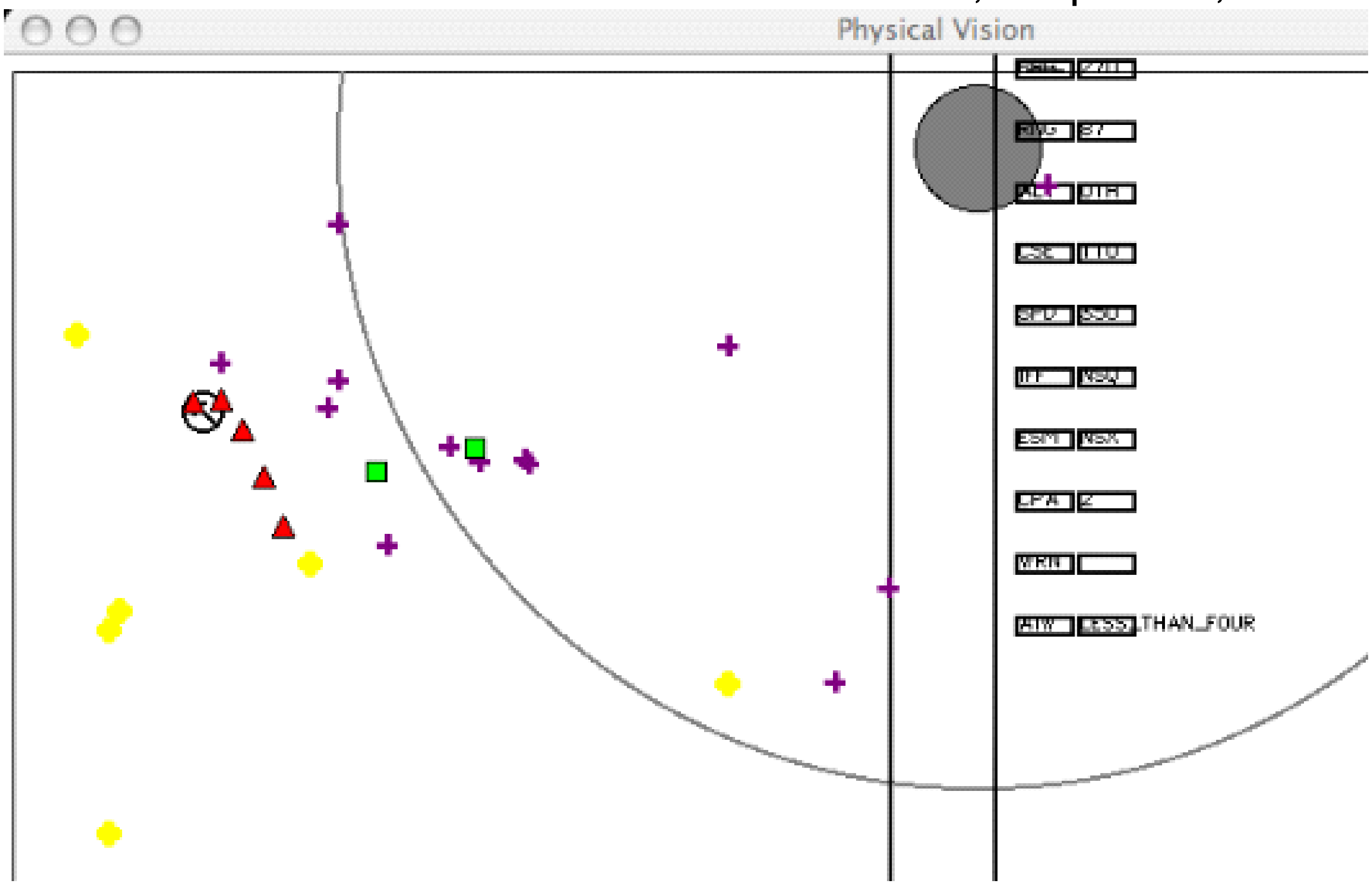
Preliminary (First Draft) MMWS Task Model Display

Physical Display presented to human simulated with EPIC.

Many “tracks” - radar blips, coded by color and shape.

Simulated human is now starting to examine the track data table.

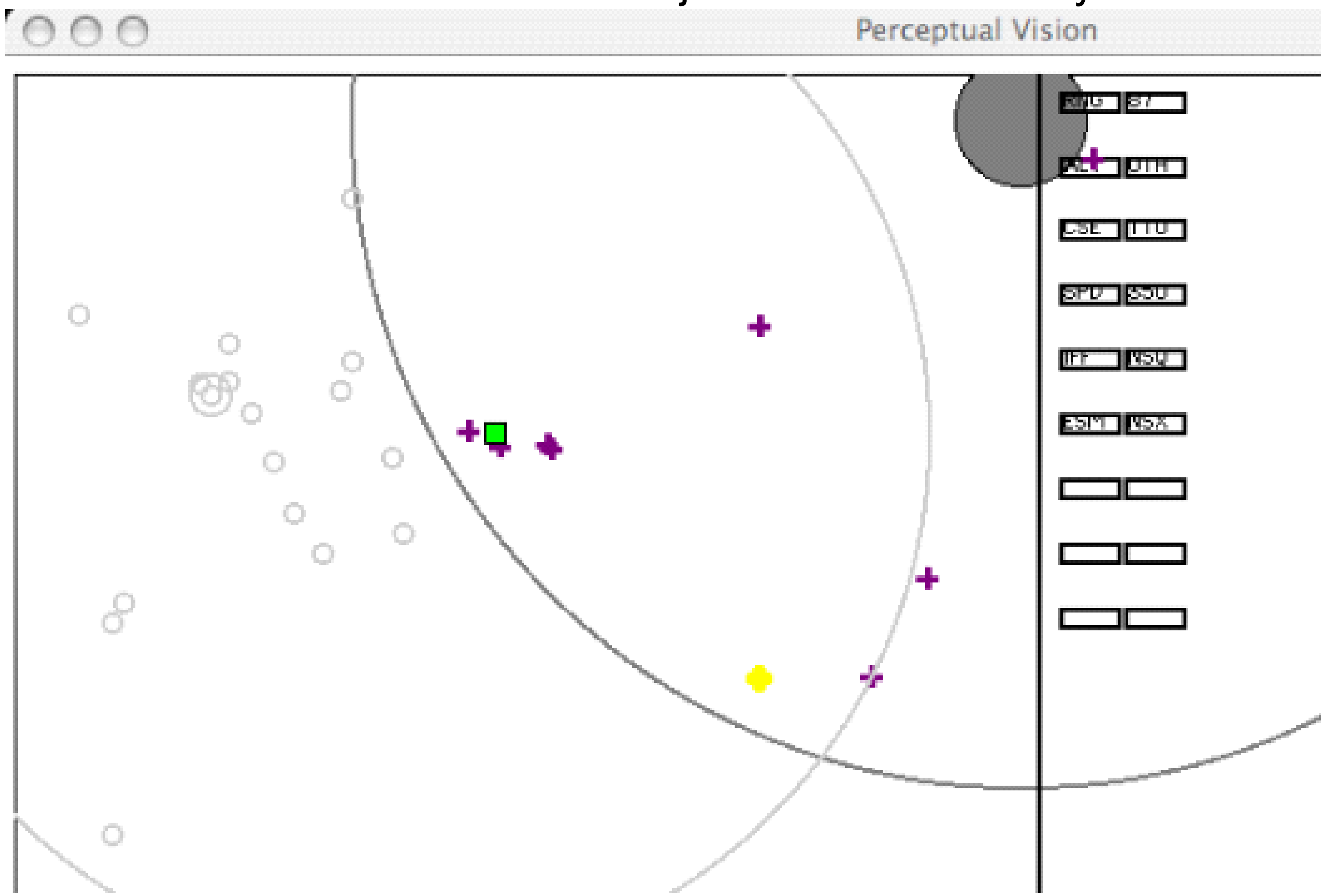
- Make decisions about whether track is hostile, suspicious, etc.



Why Visual Issues are Major

Perceptual Situation - what is available to cognition.

Distance (eccentricity) makes colors, shapes unavailable.
How much information is remembered between eye movements?
Must visual search for relevant objects start over every time?



Need: An Accurate Visual System

Visual search of a display is common subtask in many HCI application domains.

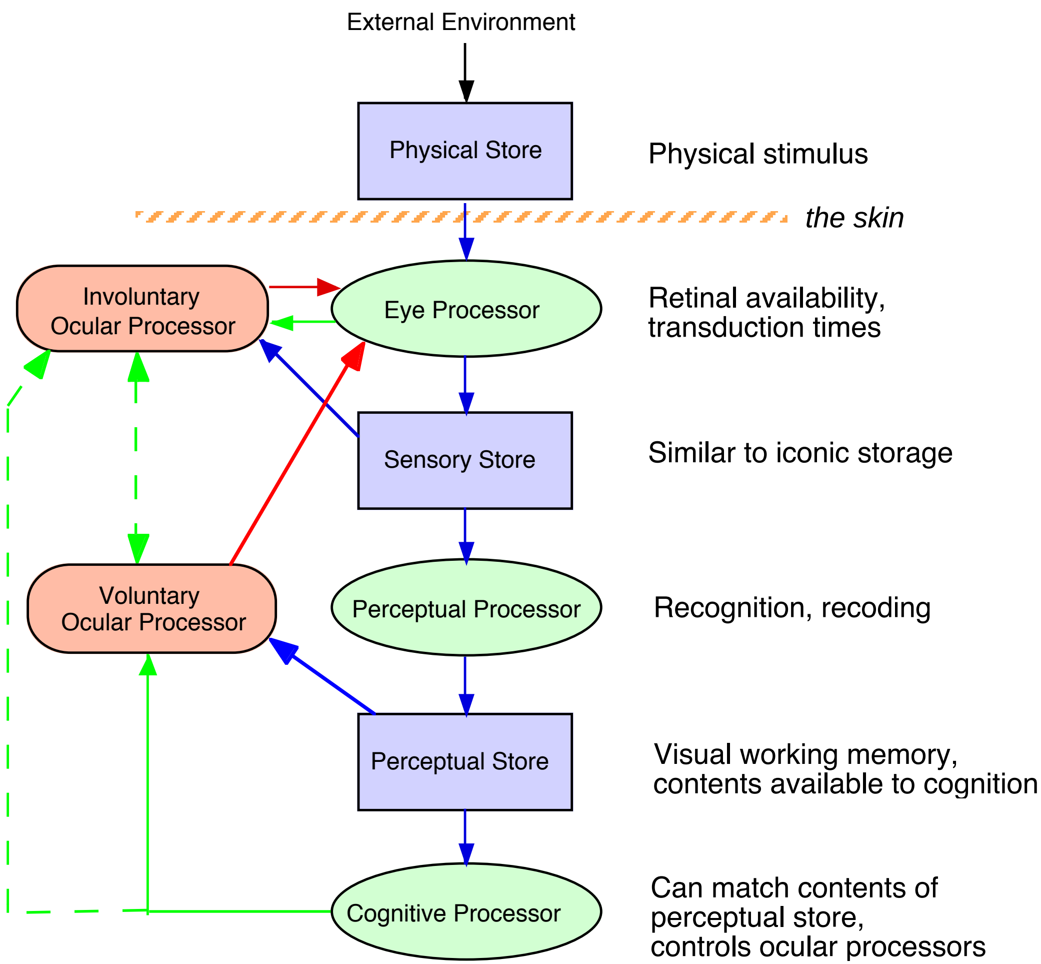
Need to be able to represent it accurately and predictively.
In these domains, "artificial" stimuli are actually "natural."
Relatively simple visual properties are relevant.

EPIC has a fully articulated visual system.

Structural components made explicit.
Easy to add the psychology of the components.

- E.g. visual memory, object-based visual mechanisms.

Current Visual System



Sub-Need: An Accurate Model of Visual Availability

Under what conditions can different visual properties of an object be perceived?

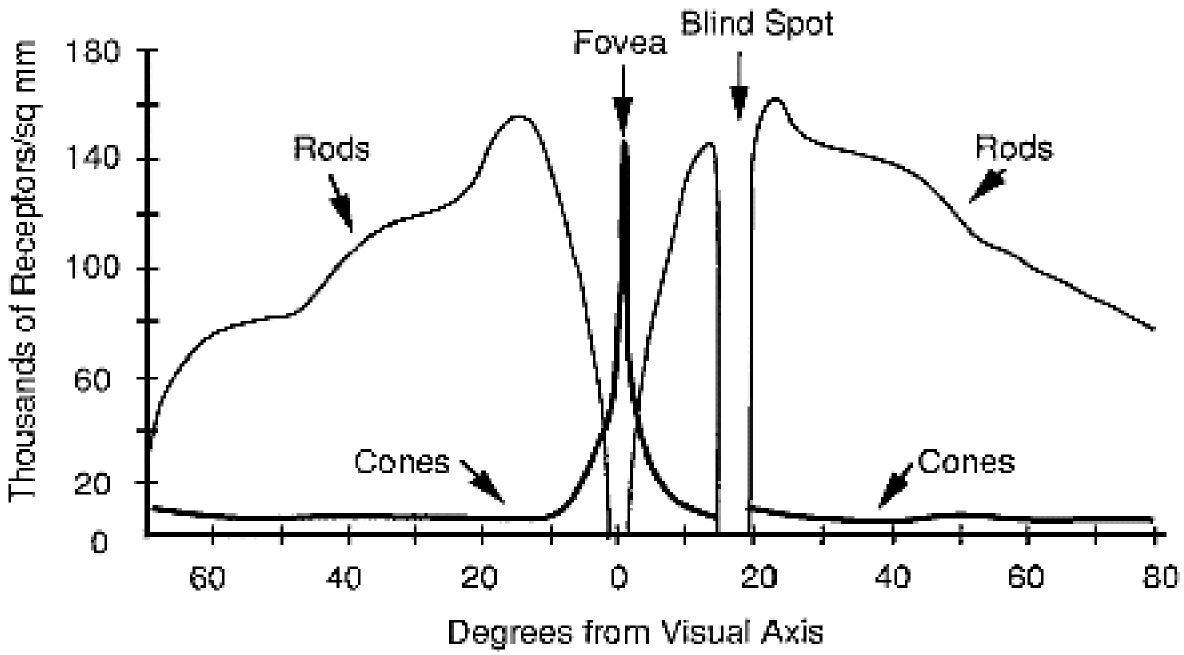
Where on the retina can different visual properties be detected?

How big, intense, etc does it have to be?

Well known that the visual system is not uniform.

E.g. receptors are not evenly distributed in the retina.

Distribution of Receptors

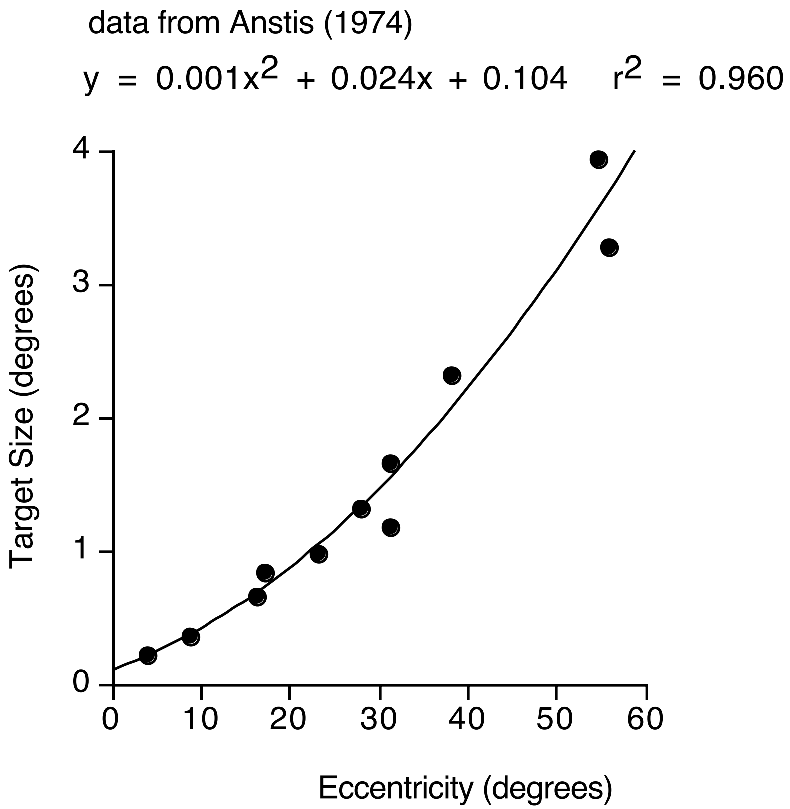


Cones - color receptors; rods - sensitive monochrome receptors.
Under "normal" HCI situation light levels, rods play little or no role in visual perception - cone system only.

Cones mostly in central 10 degees, but only thinly in periphery.
Resolution limited optically in fovea, by receptor density in periphery.

Example of Visual Availability Results

The availability of visual properties depends on eccentricity and on the size of the object.



Threshold size for recognition of a single letter.

Visual Availability Support in EPIC

Each property can have its own availability function, defined in terms of eccentricity, size, specific value, distance to other objects, etc.

But problem: What are the functions and their parameters?

Fragmented literature on availability of visual properties.
Very few parametric studies.

Approach: Model visual search tasks and fit parameters.

Visual Search Phenomena

Introduction to Visual Search

Two Visual Search Research Paradigms

Some Key Results from the Eye-movement Visual Search Literature

Active vs Passive Vision Concepts

EPIC's Active Vision

EPIC's Broadly Parallel Visual Front-end

Introduction to Visual Search

Basic Visual Search Paradigm:

Stimuli

A field of objects.
A specification of a target object.

- Typically one object is the target.

Distractors typically share some properties with the target.

Task

Find the target object that matches the specification.
Press a button or click on it when (or possibly if) target is found.

Basic data:

Reaction time.
Eye movements:

- Which distractors are looked at.
- Eye movement latencies, other timing.

Two Visual Search Research Paradigms

Even in such a specialized field, the literature is compartmentalized.

RT paradigm literature.
Eye movement literature.
Often at loggerheads.

Downside of RT paradigm:

Many issues are investigated by modifying the display on the fly or eliminating possibility of eye movements.

- Disrupt normal visual processing?
- Induce peculiar subject strategies?

RT measure is very indirectly related to the processing.

Downside of eye movement paradigm:

Difficult methodology, labor intensive, complex data.
Limited range of effects explored and documented.
Much more informative but still somewhat indirect.

Eye movement results have to be taken more seriously than RT paradigm results.

Some Key Results from the Eye-movement Visual Search Literature

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1. Eye movements are guided by specified visual properties of the sought-for object.
E.g. If a red target is specified, strong tendency to look at red objects.

2. Eye movements can be guided by combinations of visual properties.
E.g. If a red circle target is specified, strong tendency to look directly at objects that are both red and circle.

3. Eye guidance is affected by sensory-level acuity factors - "availability".
Contrast, luminance, discriminability (e.g. of shapes).
Both eccentricity and crowding effects determine availability.

4. Visual search process can "remember" visited objects well.
Sampling *without* replacement is a good first-approximation model of how objects are selected for inspection.

Active vs Passive Vision Concepts

Passive Vision

Most cognitive psychology work is done under assumptions that:

- Vision is a central cognitive process of analysis of a static image.
- Eye movements are irrelevant to understand basic visual mechanisms.
- The visual field is uniform - can ignore eccentricity, crowding, etc.
- Theoretical conclusions are thus badly skewed.

But this is most of the conventional wisdom on visual search!

Active Vision

Findlay and Gilchrist (*Active Vision*, Oxford, 2003) emphasize central importance of eye movements and retinal nonhomogeneity in normal visual functioning.

- Term from earlier computer vision literature.
- The eye is constantly moving to bring fovea to objects of interest.
- A unified view of neural systems, perceptual phenomena, and cognition.

EPIC has always been an active-vision system.

EPIC's Active Vision

An extension of fundamental properties of the architecture:
Pervasive parallelism.
Strong role played by sensory and motor peripheral constraints.
Minimal role of central cognitive limitations.
Permit heavy cognitive parallelism.
Task strategies explicitly considered.

Normally you are looking at what you are attending to, and vice-versa.
No other "visual attention" mechanism seems to be needed to account for the most important aspects of visual performance.

Decisions about what to attend to (look at) are based on:
What can be currently seen: determined by visual front-end.
Task strategy (represented in production rules).

EPIC's Broadly Parallel Visual Front-end

A large number of objects and their properties can be simultaneously present in visual perceptual store.

The amount of information available about the objects is a function of peripheral sensory-perceptual limitations, not inherent central limitations.

Depending on the specifics, considerable task-relevant information might be available, or very little.

Expect differences for different visual properties under different sensory conditions.

- No reason to expect a given property (e.g. “Shape”) to be always available (or not).

Cognitive-level decisions about the available visual information can be performed in parallel.

E.g. what to look at next, while evaluating currently fixated object.

But eye movements and responses (e.g. manual movements) must be performed sequentially.

Modeling Marshall Visual Search Task

Visual Search of Displays of Navy Symbols
Sample Display
Display Decluttering Manipulation
Sample 0% Decluttered Display with Eye Trace
Sample 75% Decluttered Display
Tradeoffs in Effects of Display Density
Current Model
Good News about RT and Number of Fixations
Good News about Fixation Durations
Mixed News about Proportion of Fixations
Worst News is about Saccade Distance
Memory for Fixated Objects
Motor Programming Problems
in the Marshall Task Models
Summary

Visual Search of Displays of Navy Symbols

Studies of effects of crowding in visual search of realistic displays using eye-tracking.

St. John, M., Marshall, S.P., Knust, S.R, & Binning, K.R. (2003). Attention management on a geographical display: Minimizing distraction by decluttering. Unpublished manuscript.

Complete fixation data set supplied by Sandy Marshall!

Objects are realistic Navy symbols for radar-type displays.

Probe object appears, then display of objects.

Subject must click on the two targets identical to probe.

Eye movements recorded during the search.

***Origin* property:**

Different colors and overall shapes.

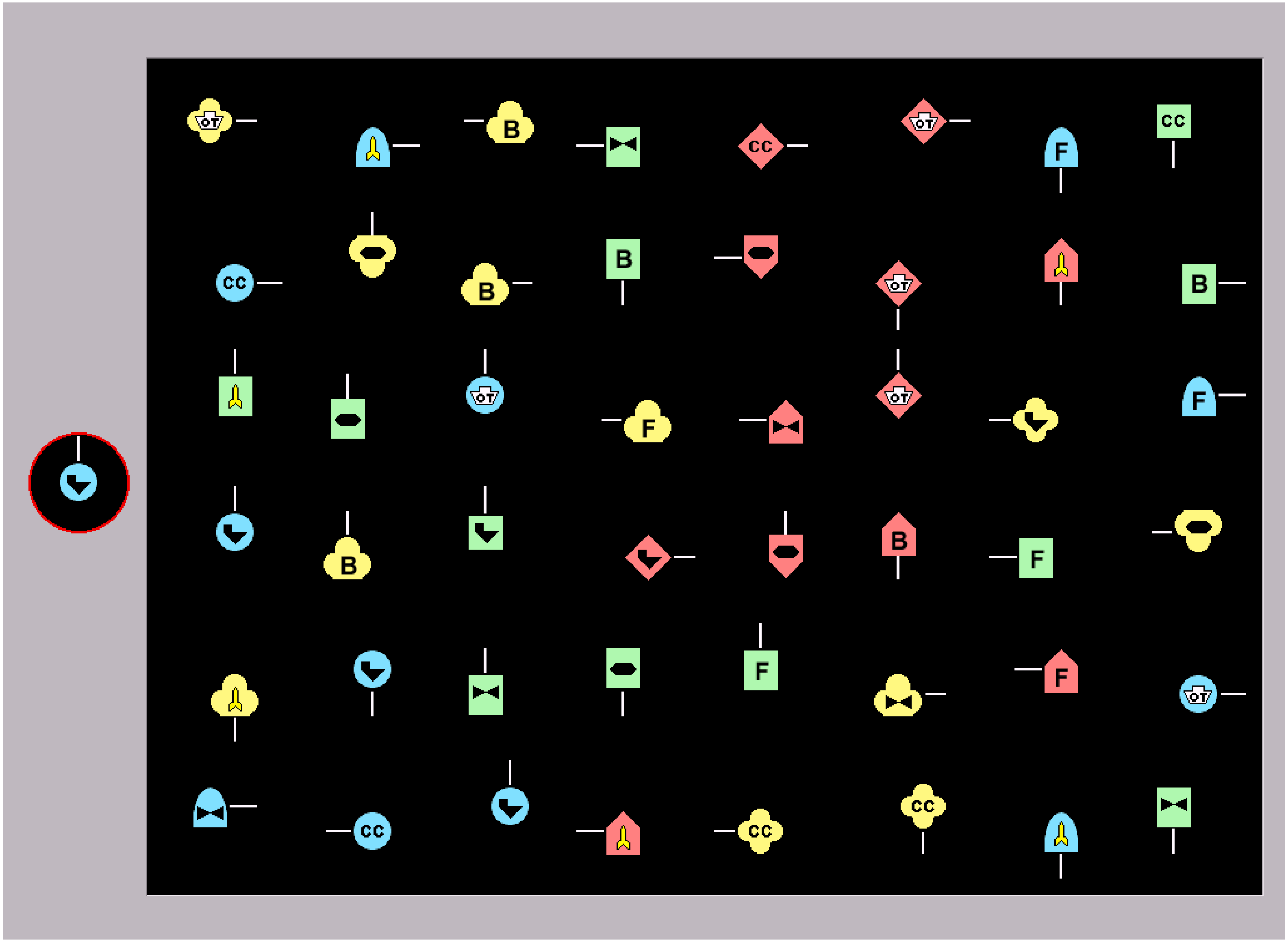
Apparently only the color is used to guide search.

***Platform* and *Direction* properties:**

Internal symbols or text labels.

“Leader lines” that normally indicate course and speed.

Sample Display



Display Decluttering Manipulation

"Declutter" manipulation: Can objects be found better if irrelevant objects "decluttered" - removed from the display in some way?

In this subset of the data, object replaced with a gray dot.

Four levels of decluttering: 0%, 25%, 50%, 75% of objects removed.

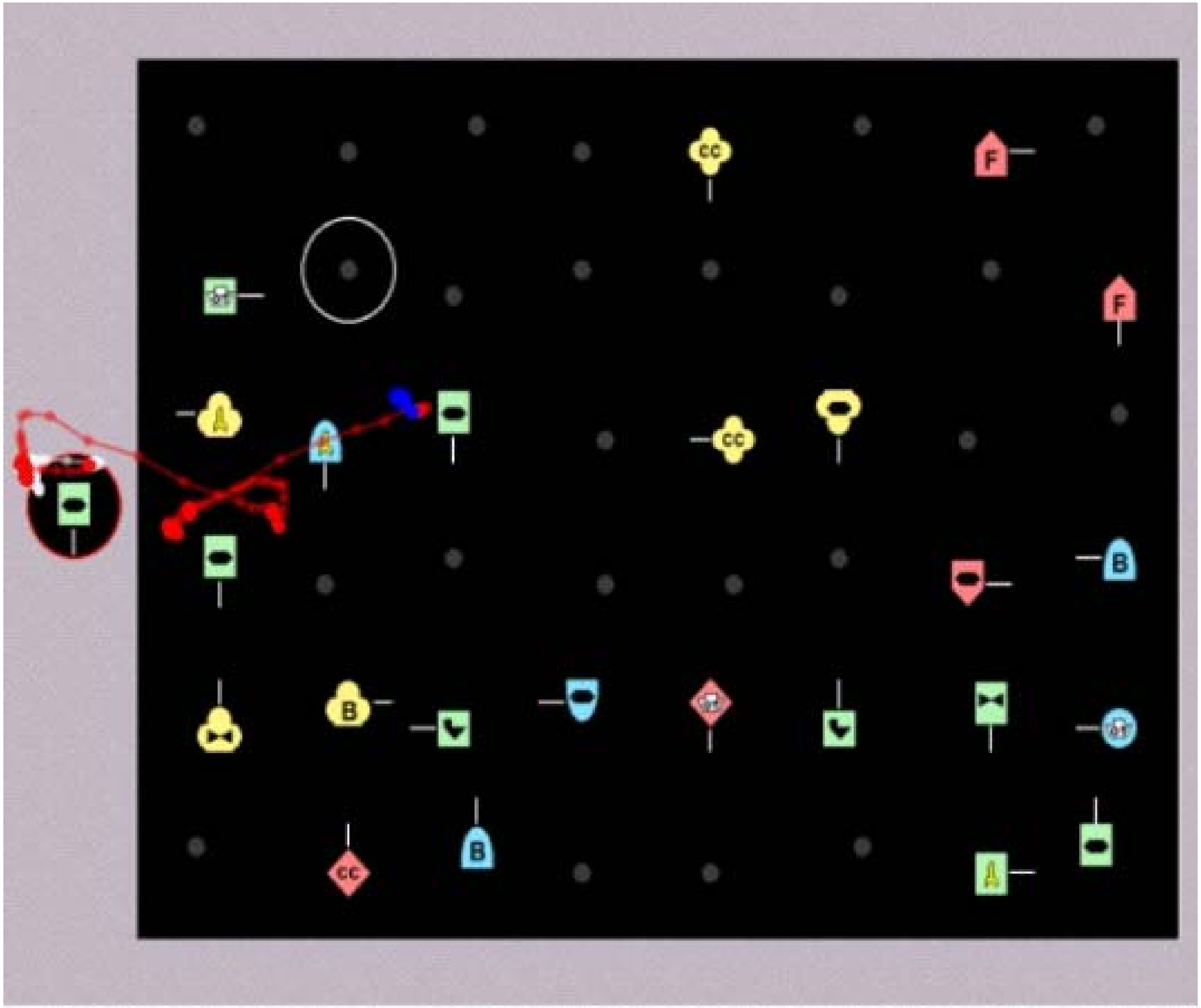
Realistic manipulation:

Highly similar distractors were always left on the display, so decluttered objects not randomly selected.

Real radar display decluttering would be based on object properties, not at random.

Sample 0% Decluttered Display with Eye Trace

Sample 75% Decluttered Display



Tradeoffs in Effects of Display Density

While always 48 objects on the screen, higher levels of declutter mean fewer icons on the screen, which on the average are further apart.

With more decluttering:
Average eccentricity greater, but average crowding less.

Crowding effects increase with eccentricity, but decrease with distance between target and crowding objects.
Bouma's rule: Area of crowding effect is eccentricity / 2
Vision literature: Area of crowding effect is larger on peripheral side of target than central side.

Thus eccentricity and crowding due to density may tend to compensate for each other.
E.g. Everett & Byrne found only very small effects of icon density in a visual search task.

Current Model

Basic strategy: Choose matching color *unvisited* object to look at; if none, choose an *unvisited* object at random.

Assume large and reliable memory for whether object has been examined.

- Will return to.

Foveal property (the label) might be mis-encoded with some probability (e.g. .08). If encoding failure detected, give that object priority to re-fixate.

- Shape, Platform, Direction available only in fovea.
- Color availability adjusted using simple zone model.

Basic result: Color availability must decrease as icon density increases in order to match the data.

Color of object available out to 9, 8, 7.5, 7 degrees as display goes from lowest density to highest density (75% to 0% decluttered).

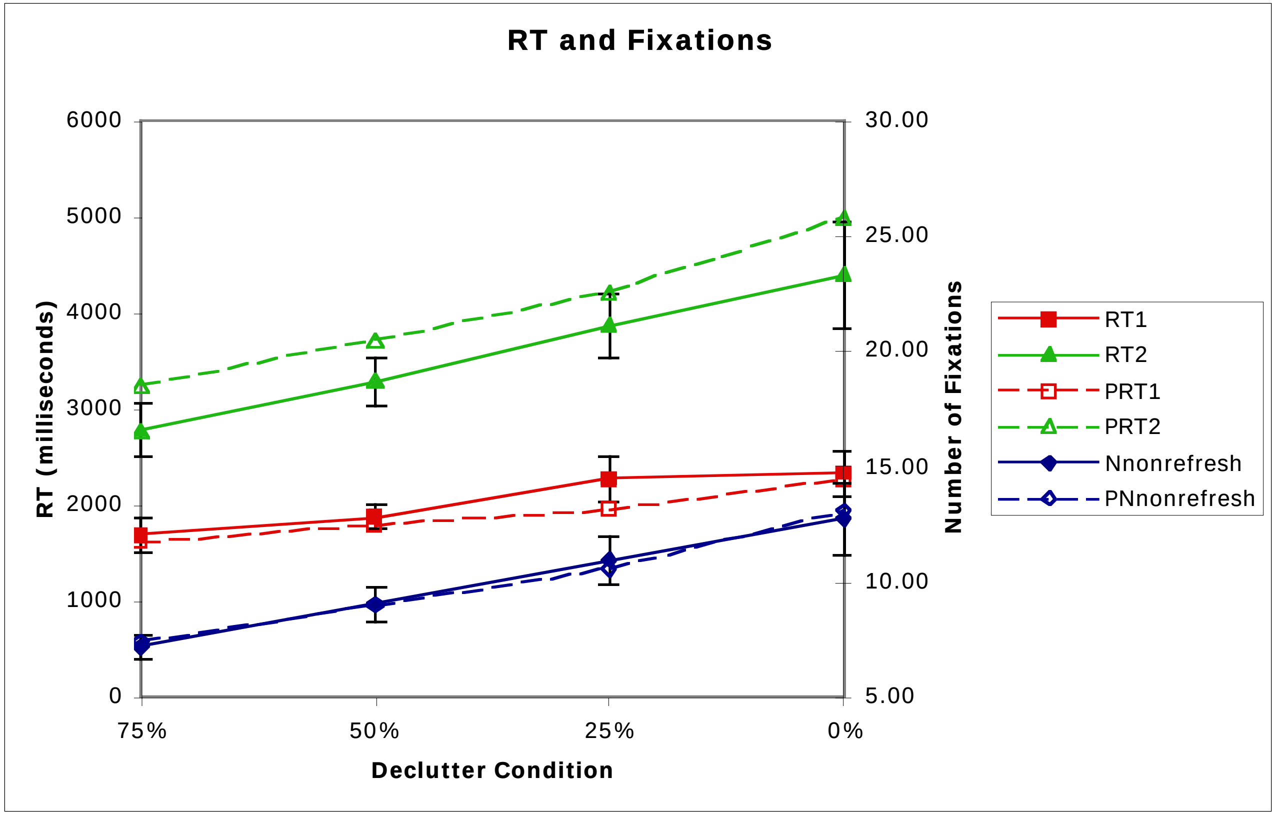
- If leave the color availability fixed at a single value, get gross misfits at some decluttering levels.

These are approximate values that could be used in modeling similar displays.

E.g. the CIC Radar Operator Task.

Compute availability dynamically as a function of local density of each object.

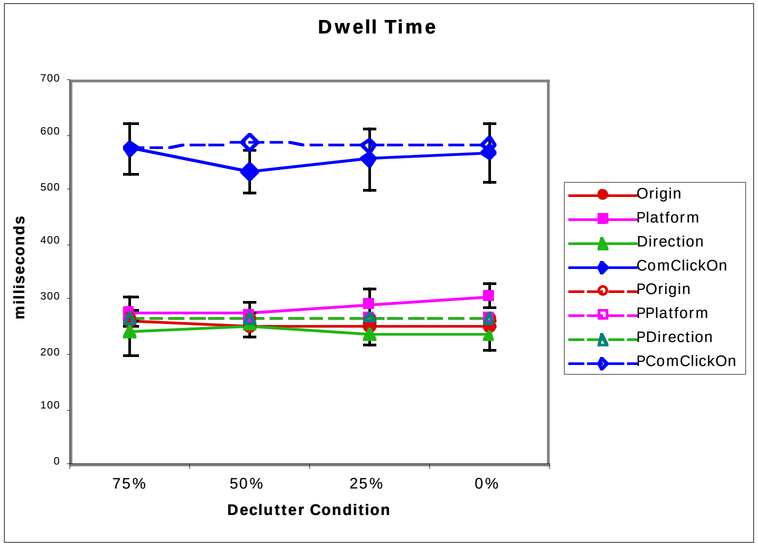
Good News about RT and Number of Fixations

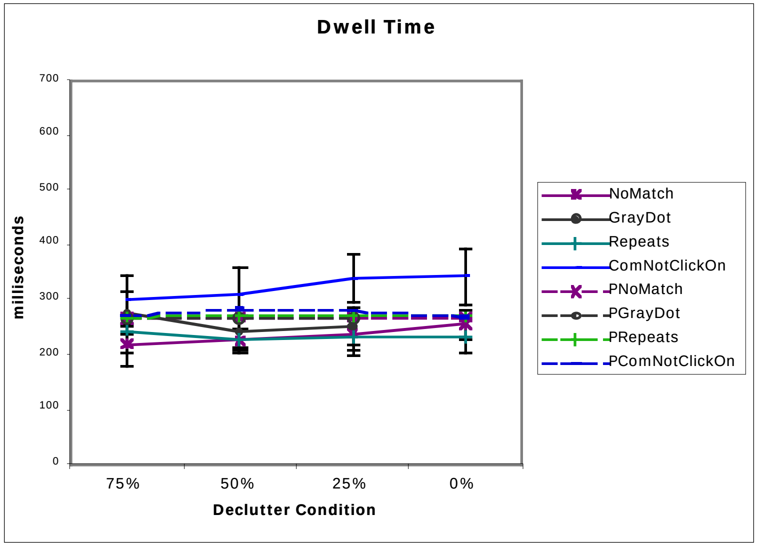


RT to second target is faster than predicted - some evidence in the data that eye goes ahead before click-on is complete - could match it.

Good News about Fixation Durations

Fixation Durations ("dwell" time) is about right - governs basic relation between number of fixations and RT.

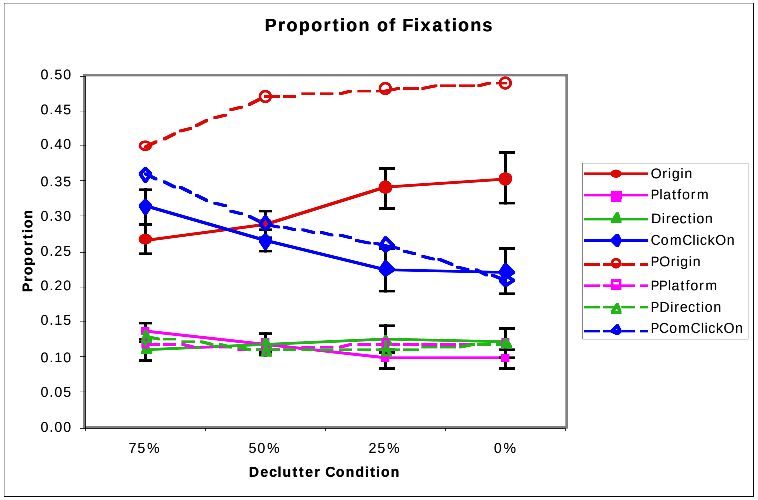


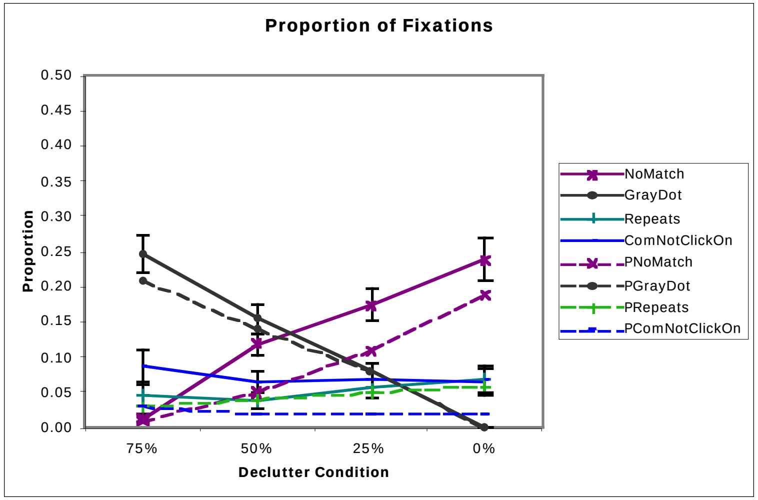


Fairly constant with declutter level.

The 250 ms time is pretty typical in the literature.

Mixed News about Proportion of Fixations





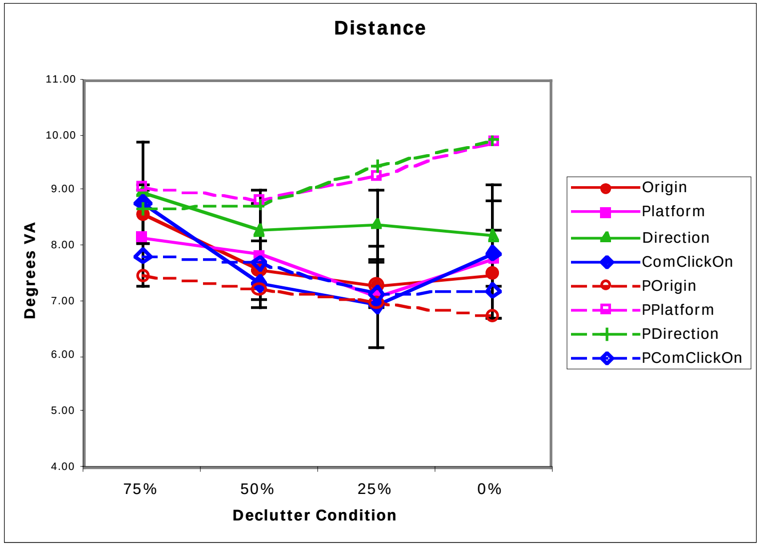
Color-guidance is too strong: Model looks at same-color targets more often than it should.

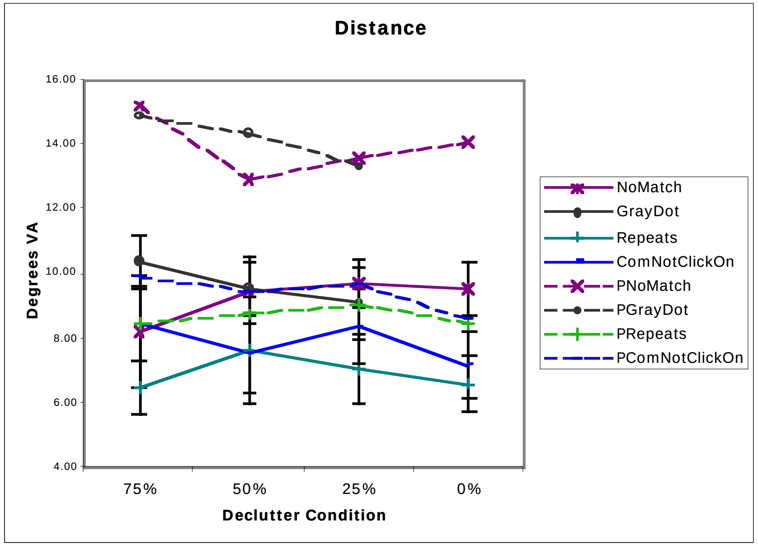
Not often enough at objects that don't match any properties.

Too few repeat fixations - more parameter adjustment?
"Double checking" of targets - a different repeat mechanism.

Worst News is about Saccade Distance

Overpredicted for saccades unguided by color.





Model makes "guesses" by choosing an object at random from the entire display, spreading out the searched area.

Currently, availability of objects is independent of eccentricity.

"Objecthood" is always perceived.

Should decrease with eccentricity - cf. various results in the literature.

Eccentricity + Crowding => objects “smoosh together” in the periphery.

Memory for Fixated Objects

Conventional wisdom in cognitive psychology is that visual search has no memory (Horowitz & Wolfe, 1998).

Still maintained with few qualifications (e.g. Wolfe, 2003, 2005).
Was demonstrated with RT paradigms and changing displays.
Several counter-arguments and demonstrations in the literature.

Key eye movement study: Peterson et al., 2001.

Under conditions where foveation of targets is necessary and 12 targets, only a 5.7% refixation rate!

- Statistical structure of data is essentially sampling without replacement.
- Most refixations are after one intervening object, possibly a result of encoding failures.
  - Used in Marshall model.
  - Can model the Peterson task this way as well.

Modified model with no-memory and "passive vision" assumptions fits some aspects of data well, others very poorly.

Predicts number of fixations well, RT passably - interesting!
Grossly overpredicts the number of repeat fixations.
Grossly underpredicts the number of fixations on mismatching objects.
Conventional wisdom bites the dust in this task.

Motor Programming Problems in the Marshall Task Models

Cascade effect of many fixations and two mouse movements.
Even a little bit of time error will add up.

To get the latencies and dwells even approximately right, had to assume zero feature programming time for both saccades and mouse pointing movements.
Also in models for other tasks ...

In addition, much faster mouse moves because effective pointing target much larger than icon size.
How the experimental software actually works.
Now can specify effective target size instead of using visible object size to motor processor.

Summary

EPIC's mechanisms scale up for realistic displays.

EPIC's high-capacity parallel visual system again can account for data.
Visual parameter values useful for the MMWS task displays.

Visual properties are important in task performance:

Both eccentricity and crowding effects are present, leading to relatively small effect of display density on availability.
Most salient visual property (color) can be used in visual search of crowded displays with complex objects.

Conventional wisdom is wrong:

Memory for previously fixated objects is large; few refixations.

- Wolfe's no-memory guided search model cannot account for effects.

Eccentricity/crowding effects are present and must be represented.

Both eye movements and aimed manual movements appear to be programmed very rapidly.

Problems with Motor Feature Programming

Basic Motor Feature Programming Concept
Is there Something Wrong with EPIC's Motor Processors?
Where We are Going

Basic Motor Feature Programming Concept

Motor movements must be programmed before they are started, in terms of some number of motor features, each of which are serially prepared.

A movement can be initiated faster if the features are prepared in advance using precues to the movement, or remembered from a previous movement.

Popularized by Rosenbaum (1980); has become "conventional wisdom" in motor control field.

Adopted for EPIC as capturing key constraints provided by motor processes in human performance.

EPIC's motor processes compute and compare motor features to determine the motor preparation time.

- 50 ms for each feature that must be prepared anew for a movement.

Is there Something Wrong with EPIC's Motor Processors?

If we really need zero movement feature programming time to match the visual search data, then something is wrong.

Do we need to make this change to the motor processors?

Let's go back and look at the basis for movement feature programming.

Some background on what the classical results show, and what some newer results show.

Sorry, a bit of literature review of low-level tasks.

But a major change to the architecture can't be made lightly!

Also instructive to see how conventional wisdom can go off the rails.

Where We are Going

Claimed motor feature programming effects are apparently a result of translations due to poor S-R compatibility - actually a Hick’s Law effect.

S-R compatibility: Similarity of stimuli and responses in a relevant way.

- If response is enough like the stimulus, RT will be faster.
- Spatial compatibility - similar location pattern for stimuli and responses.

Hick's Law: Reaction time in a choice reaction task is linear with the log(2) of the number of alternative choices (amount of information transmitted).

- Ancient result (1952).
- Only appears if S-R compatibility is moderate or poor.

Once a visual target has been identified, an aimed manual movement or an eye movement can be quickly launched to it without any S-R translation or motor feature programming delays.

Illustrate with focus on aimed manual movements, then skim over eye movements.

Aimed Manual Movement Programming

Aimed Manual Movements: Rosenbaum (1980)
Rosenbaum's Task
Rosenbaum's Results
Response Selection Effects?
But still ...
Goodman & Kelso (1980)
Goodman & Kelso Compatible Task
Rosenbaum vs. Goodman & Kelso Results
Per-Feature Time Depends on Compatibility
G&K: Hold Number of Alternatives Constant
Number of Alternatives Dominates
Hypothesis: Rosenbaum's precuing paradigm is actually a "dynamic Hick's Law" paradigm.
Making Aimed Movements More S-R Compatible
Dassonville, et al. 1999.
Wright (2004): No Hick's Law Effects
for Pointing Movements
Conclusion for Aimed Manual Movements

Aimed Manual Movements: Rosenbaum (1980)

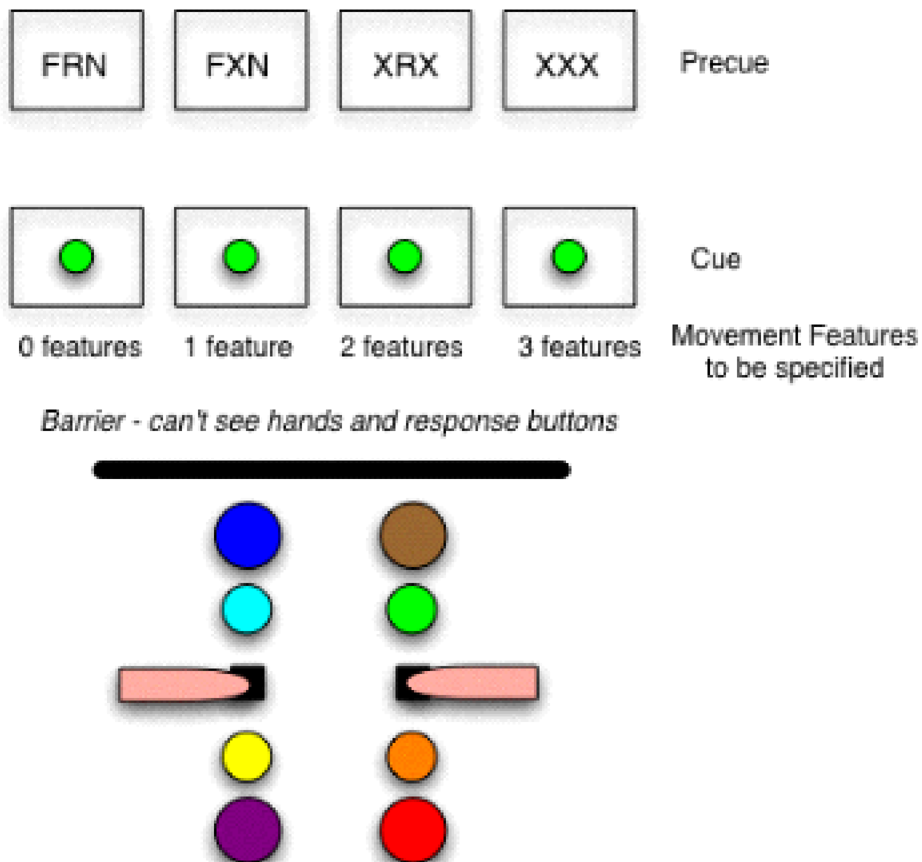
First major presentation of the motor feature programming concept.

Precue arm, direction, extent (distance) features for pointing movement to a target, then measure RT to a specific cue.

Manipulate number of features that are precued, which changes how many features have to be computed before starting to make the movement.

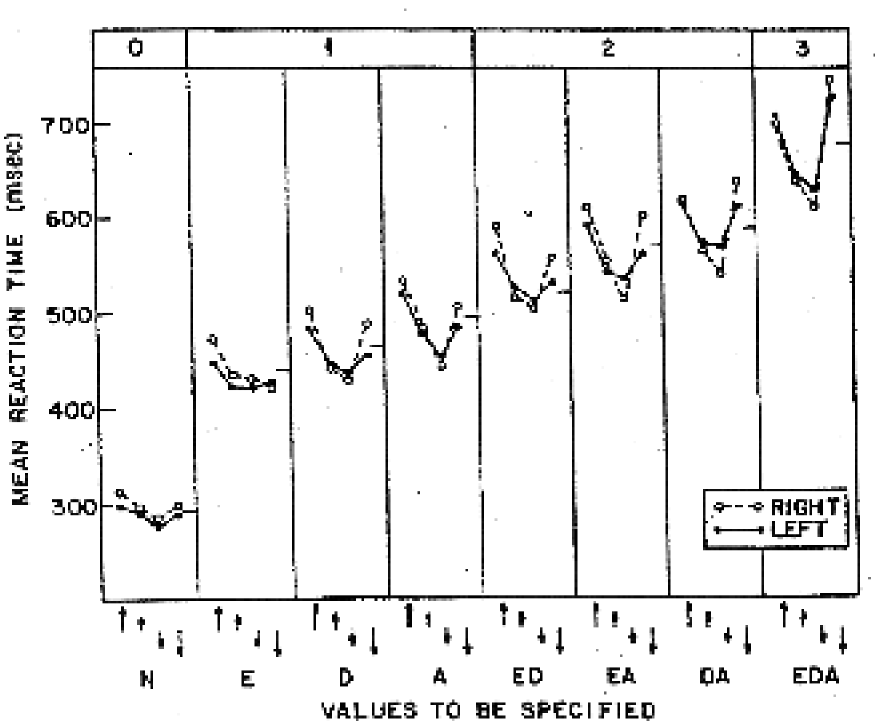
Movement targets identified via memorized color codes; movement precues given by text codes.

Rosenbaum's Task



RT is time when finger leaves “home” button.

Rosenbaum's Results



Movement RT increases with number of features that must be specified by the cue.

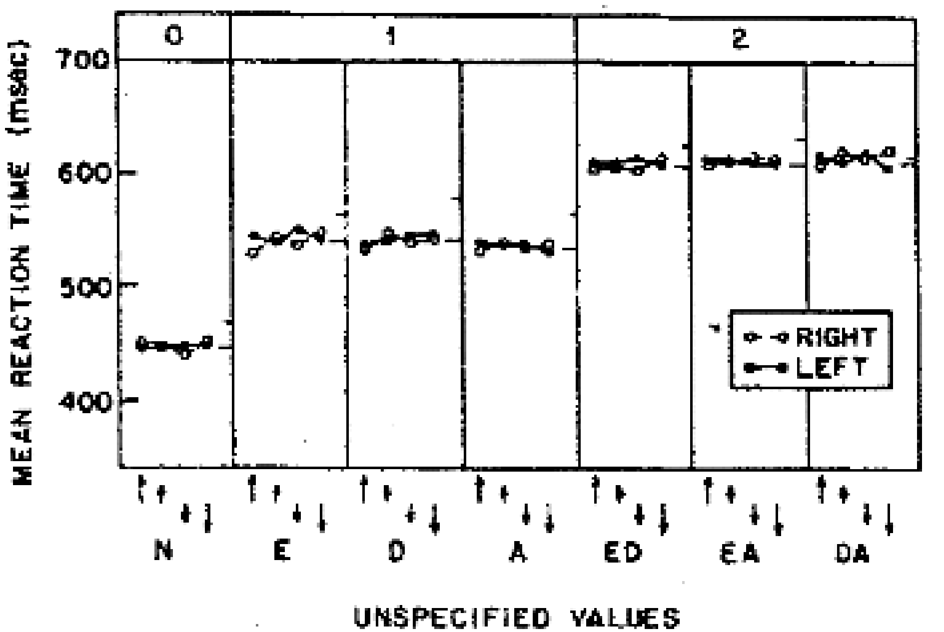
No such effects on the execution time for the movement.

Also, some feature and movement-specific effects.

Response Selection Effects?

Were effects due to differences in processing the precue and cue information to identify the movement target?
Rosenbaum's "stimulus identification" process.

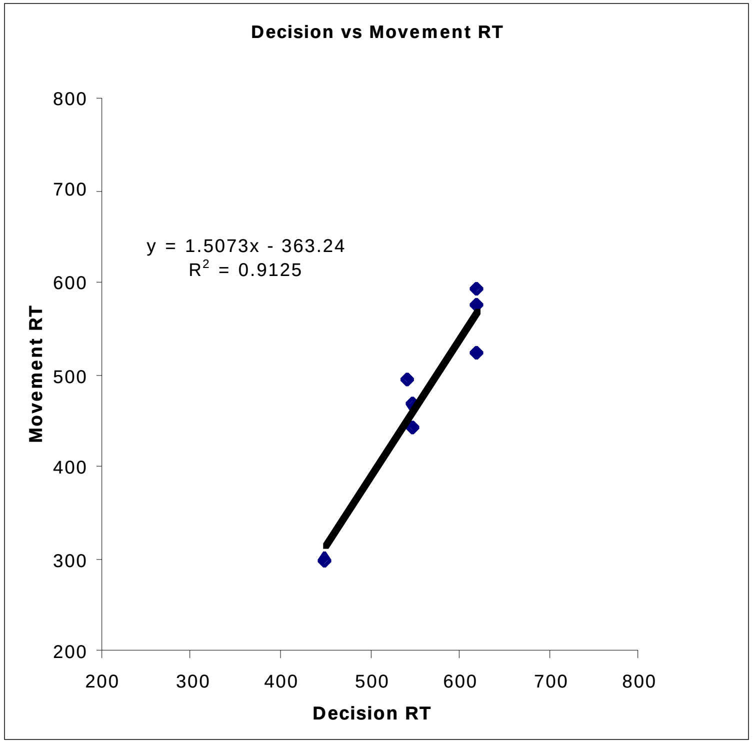
Use decision task instead of button-pressing.
Subject had to respond (by voice) whether cued movement was a valid target given the precue.



Effect of number of precued features, but nothing else.
Rosenbaum: Not an important component of the movement RT.

But still ...

Movement RT is clearly related to the decision RT.
91% of variance in mean movement RT for each feature type is accounted for by mean decision RT.



Suggests that a lot of the RT is actually due to response selection.
Doesn't explain the movement-specific effects, but they are quite small by comparison.

Goodman & Kelso (1980)

First, replicated Rosenbaum's results using color words or numbers instead of presented color dot cue.

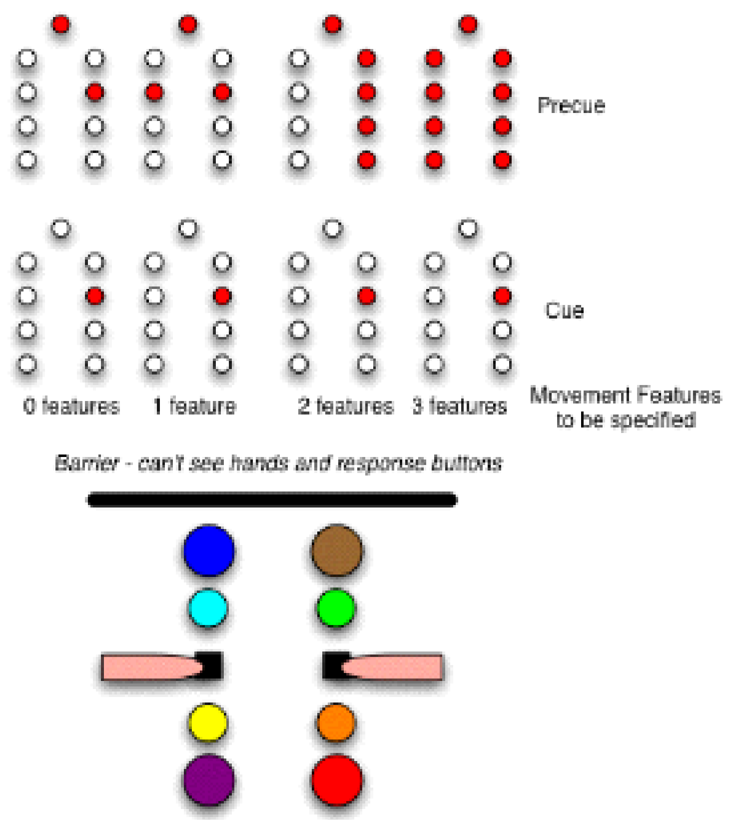
Then used precues and target cue presented in fairly spatially compatible way.

Light panel above response board with light layout matching button layout.

Result: More compatible task considerably diminished effect of precues, no movement-specific effects.

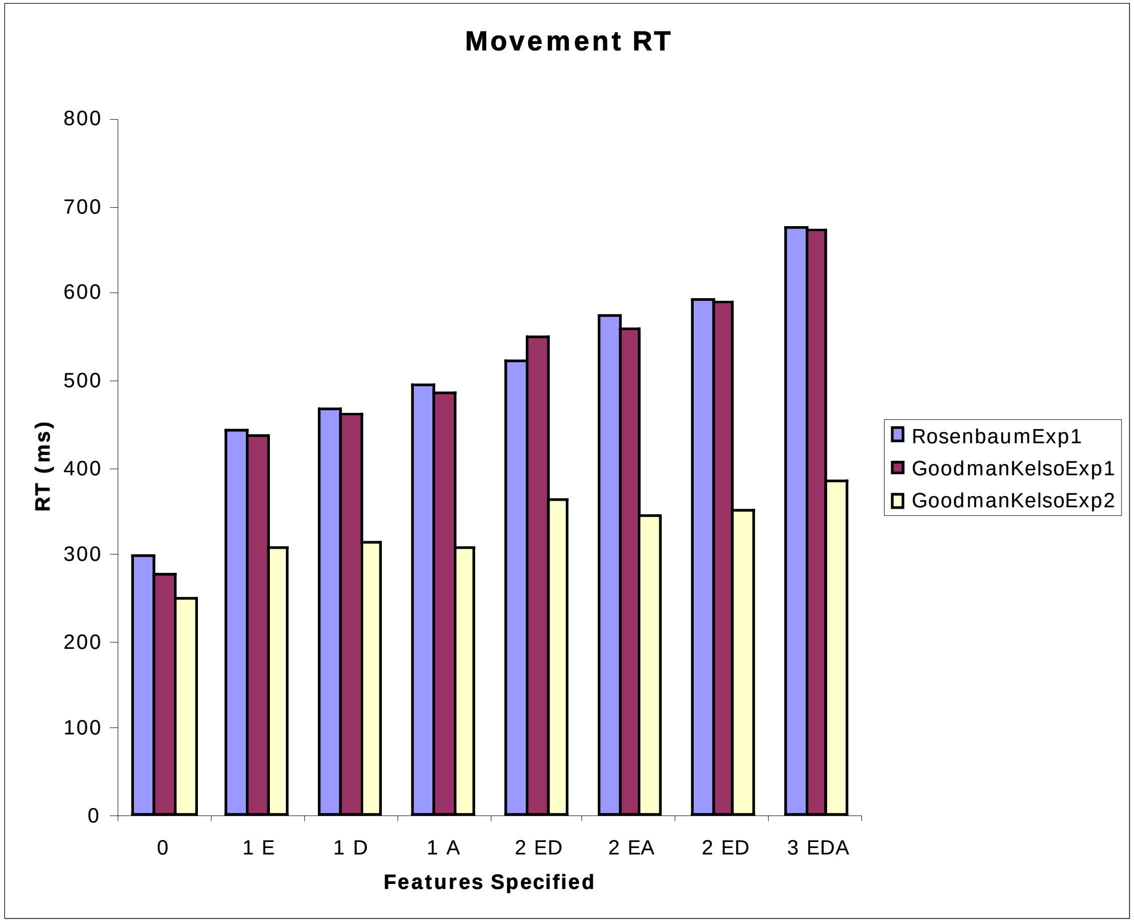
Why would motor programming depend on S-R compatibility?

Goodman & Kelso Compatible Task

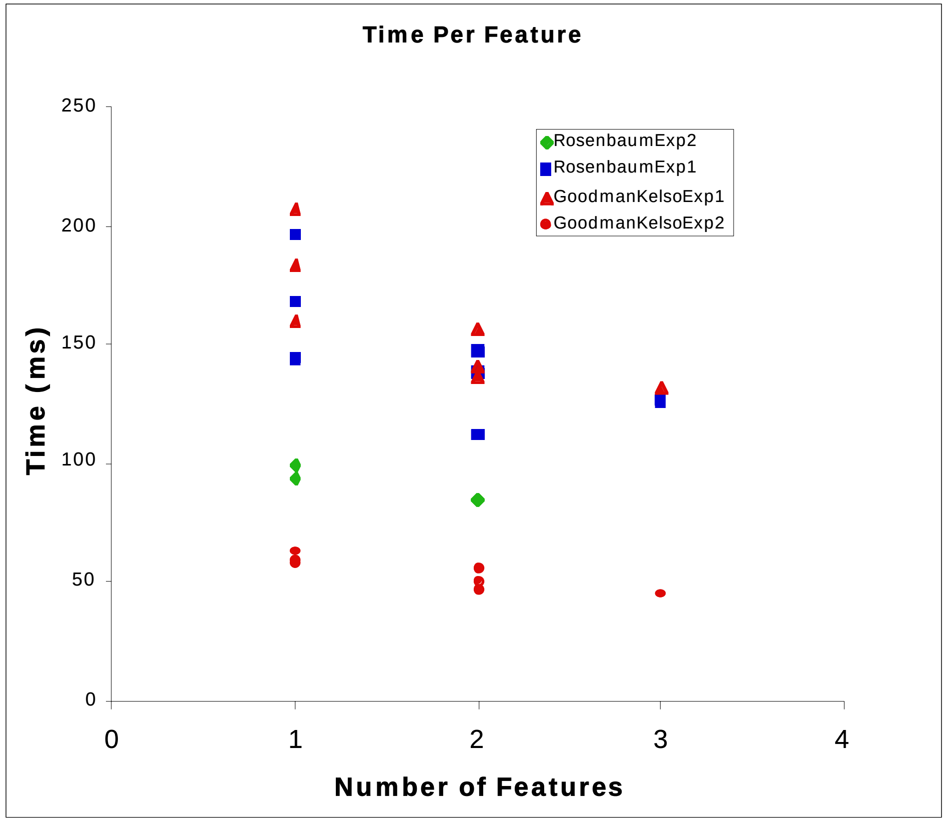


Light panel mounted vertically above horizontal button board.

Rosenbaum vs. Goodman & Kelso Results



Per-Feature Time Depends on Compatibility



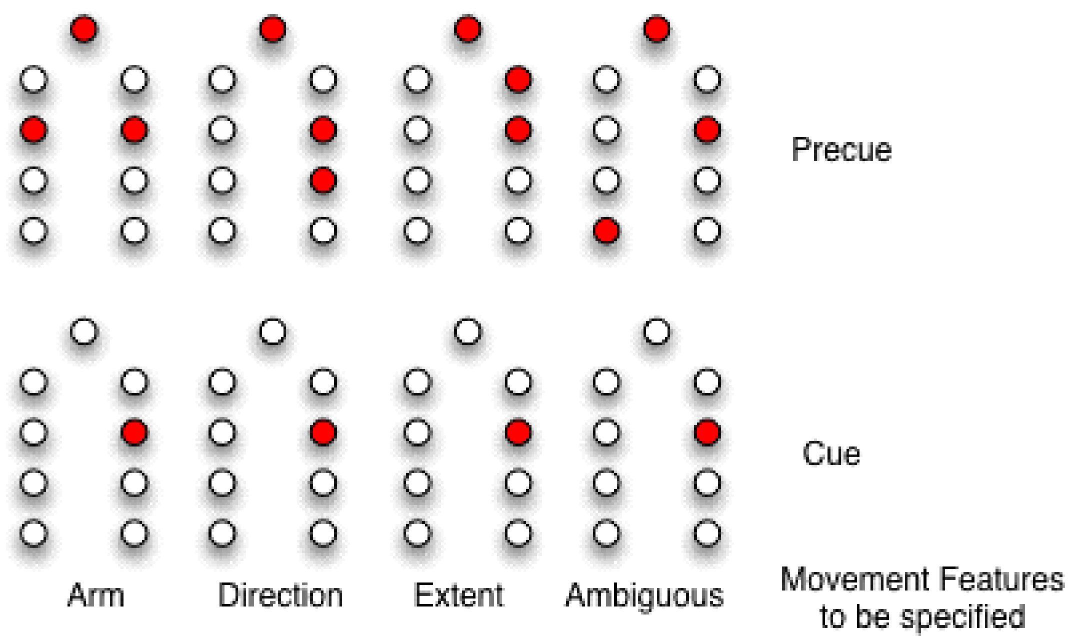
Not supposed to happen! Optimistic interpretation:
50 ms per feature is actual motor time; rest is response selection.

However, S-R compatibility isn't perfect in the task; could the feature time actually be minimum response selection effects?

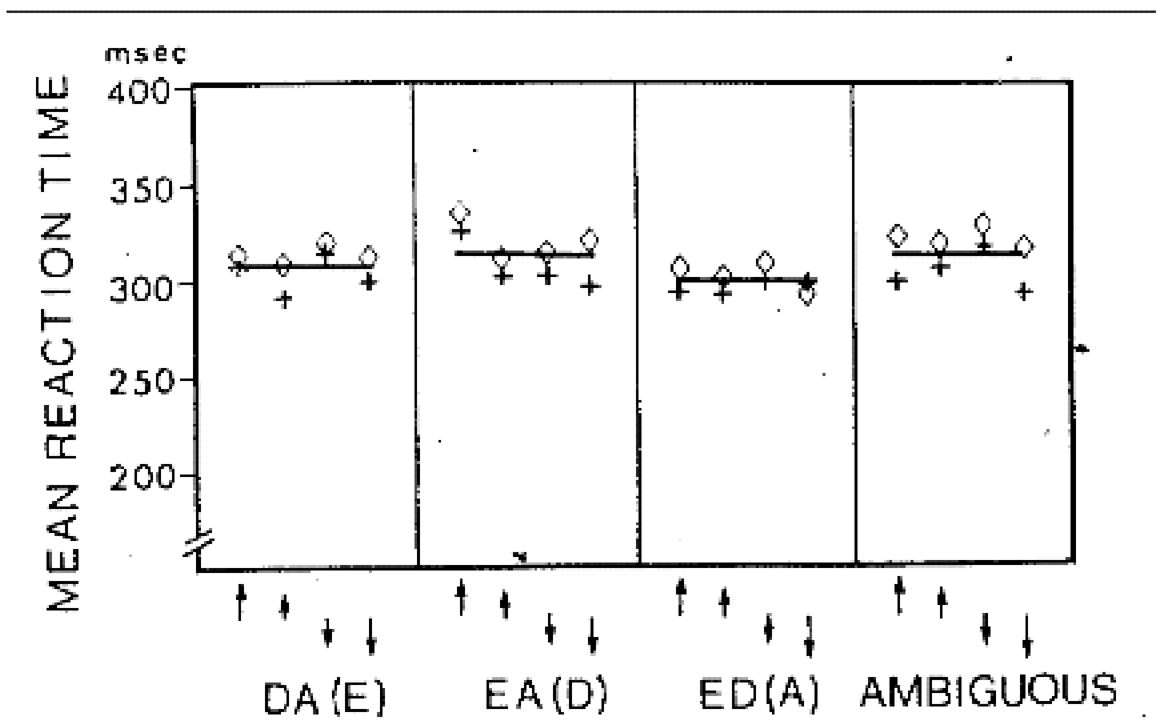
G&K: Hold Number of Alternatives Constant

If response selection effects, shouldn't depend on motor features.

Include ambiguous precue: cue both values for the same feature:
Ambiguous features, but specifies possible targets.



Number of Alternatives Dominates



RTs are the same - the set of possible targets is relevant, not the movement features.

This is now looking more like a Hick's Law paradigm, isn't it?

Hypothesis: Rosenbaum's precuing paradigm is actually a "dynamic Hick's Law" paradigm.

Direct correspondence between:

- Number of features that not precued.
- Number of alternatives specified by the precue.

On each trial, specify the number of responses by specifying the possible targets by means of feature precues.

When the stimulus is presented, the response is thus one of the possible targets.

Hick's Law: RT is linear with log(2) of number of alternatives, with the slope depending on the S-R translation required.

RT for 2, 4, 8 alternatives is thus linear under Hick's Law.
Ancient result (1952).

Goodman & Kelso compatible task might still require some S-R translation for response selection.

Making Aimed Movements More S-R Compatible

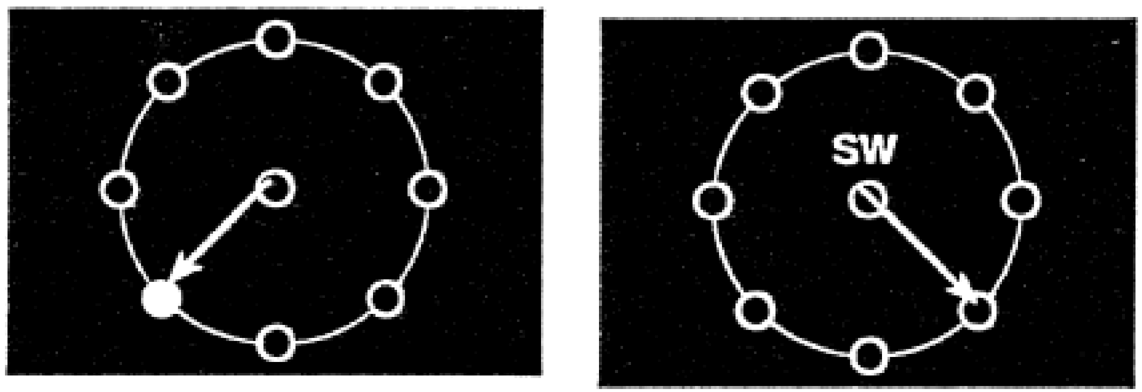
Old result: If the stimulus directly identifies the response (e.g. name digits), then number of alternatives irrelevant, Hick's Law slope is 0.

What happens in aimed movements?

Make stimulus location identical with target of movement - can't get any more spatially compatible than that!

Dassonville, et al. 1999.

Make joystick movements to visible targets with different mappings:
Most compatible: Move directly to target.
Least compatible: Move to target at 90° counter-clockwise from position given by symbolic code (e.g. SW).



Varied number of alternative targets (2, 4, 8).

In highly compatible mapping, no effect at all of number of alternatives on RT. Hick's Law slope is zero.
Latency: about 300 ms.

If S-R pair repeated, no effect on highly compatible mapping, but substantial effect on incompatible mappings.
Suggests that repetition benefit is due to remembering results of response selection, not previous motor features.

Wright (2004): No Hick's Law Effects for Pointing Movements

Stimuli - a set of circles arranged in an arc.

Response - point with stylus to the circle that turns white.

Compared 2 versus 6 alternatives.

Results: Mean RT for N=2 is 254 ms, for N=6 is 257 ms. No Hick's Law effects.

Little or no effect of repetitions - suggests no remembered response selection results.

Compared onset stimuli with equiluminant color-change stimuli: No difference.

Argues against some kind of automatic onset-triggered movement.

Conclusion for Aimed Manual Movements

Motor feature programming effects are most likely a result of translations due to poor S-R compatibility - actually a Hick's Law effect.

Once a visual target has been identified, an aimed movement can be quickly launched to it without any S-R translation or motor feature programming delays.

Eye Movement Programming

Eye Movements: Abrams & Jonides (1988)

Classic follow-up to Rosenbaum.

But with saccades instead of arm movements.

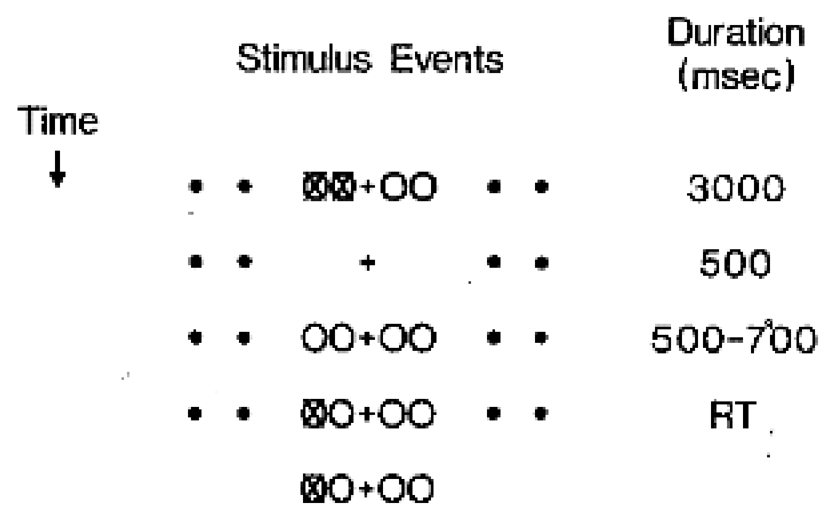
Paradigm:

Anti-saccade: Cue is opposite direction of required movement.

- So cue stimuli are mirror-imaged from required response.

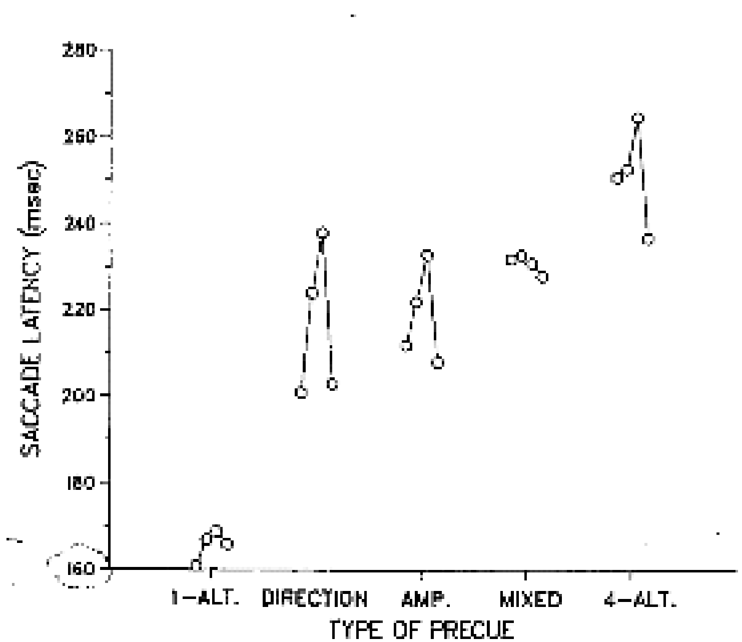
Compare cues of different types:

- Direction, amplitude, ambiguous, uninformative.



Targets are removed as soon as eye movement started.

Abrams & Jonides Results



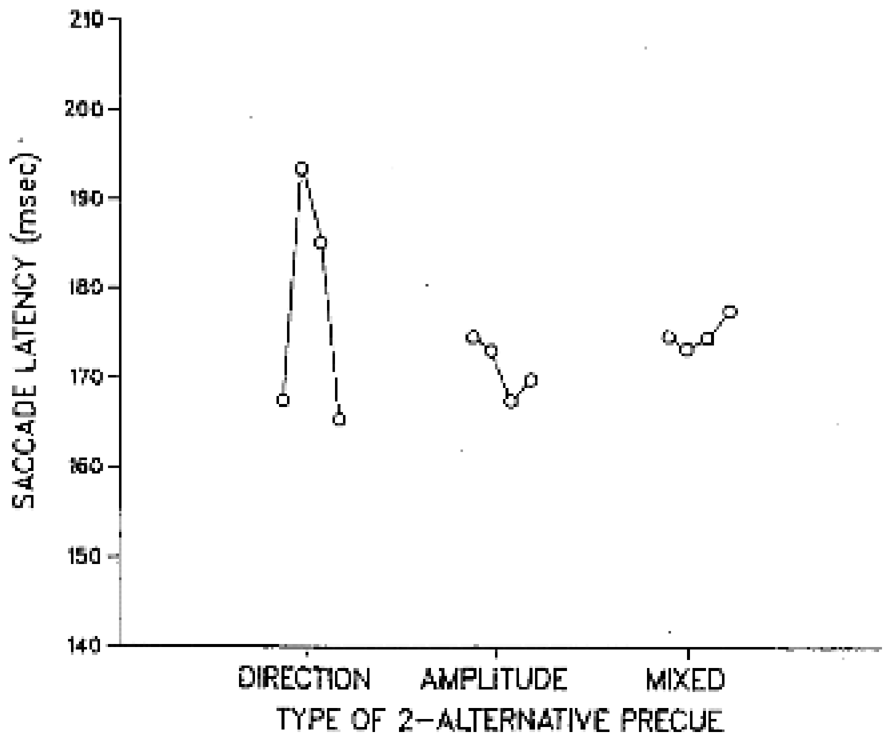
Some movement-specific effects, but 50 ms/feature benefit.
Mixed (ambiguous) cue was 13 ms slower, which was significant.
But should be a lot slower if uninformative.
But anti-saccades mean poor S-R compatibility.

Compatible Task, Only Two-alternative Cues

Cues made compatible with responses.

Mean latencies the same for ambiguous precues as other cues that identify two alternative targets.

Number of alternatives, not number of features, dominates.



Some movement specific effects.

Crawford & Mueller (1990)

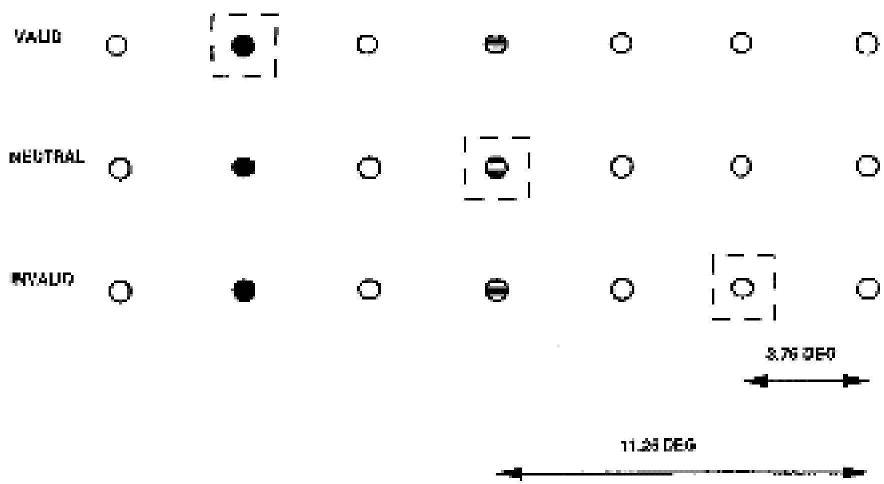
Totally compatible precues and cues.

Cues and targets are lights at the actual target locations.

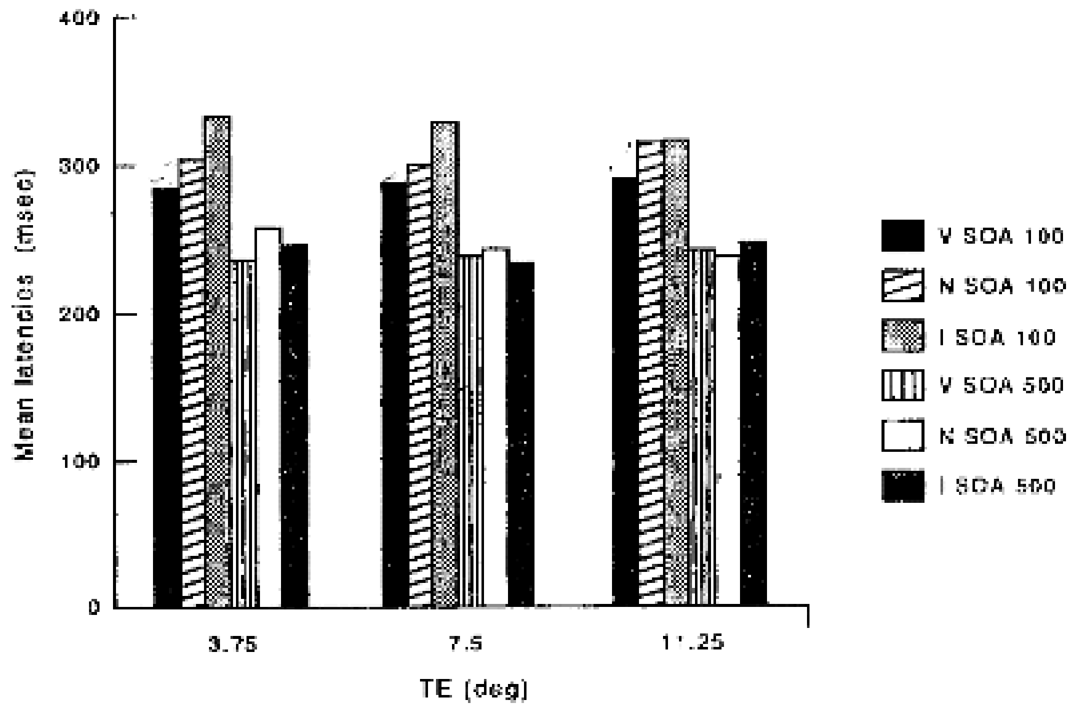
Precue: background lighting a possible target location.

- Valid, invalid; different positions.

Eye movement made to onset light.



Results



At SOA 500 ms, precuing is no benefit, latencies equally fast.

About 250 ms.

Small benefit at SOA 100 ms.

Not expected given motor feature precuing concept.

Due to high S-R compatibility?

Response Selection Effects in Saccades?

Yes, Hick's Law effects if incompatible mapping:

Lee et al. (2005): saccades to remembered locations in a circular array identified by memorized color codes (shades of Rosenbaum!).

No Hick's Law effects if stimulus is co-located with target:

Kveraga et al. (2002, 2005): zero Hick's Law effects in saccades to targets in a circle or semicircle.

- But did get Hick's effects for anti-saccades (look in opposite direction) or key presses to the same stimuli.

Are these "reflex" saccades to target onsets?

Persistent concern in this literature - onset triggers a saccade to it.
Kveraga:

- Stimulus is not full onset, but visible circle is filled in.
- Latency strongly depends on brightness of an onset stimulus, but Hick's Law effect still missing even in targets barely above threshold.

Findlay's results argue against reflex saccades.

All objects onset at once; target chosen cognitively; RT is still only 250 ms. By usual Hick's Law coefficients, expect it to be a lot slower.

Conclusion for Eye Movements

Same pattern as with aimed manual movements:

Motor feature programming effects for eye movements are also probably Hick's Law effects.

Once a visual target has been identified, an eye movement can be quickly launched to it without any S-R translation or motor feature programming delays.

Status of Motor Movement Feature Programming

Recap of Motor Feature Programming Problem
Motor Features in Other Manual Movements?
Golden Oldies: S-R Pair Spatial Effects
Our Results on Fast Learning of Individual S-R Pairs
What is Learned in a Simple Choice Task?
Changes to EPIC Motor Processors

Recap of Motor Feature Programming Problem

Difficulty in matching times in high-speed and complex realistic visual search tasks suggests that motor processors are too slow.

A re-examination of the motor processing literature suggests that the motor precuing paradigm is actually a Hick's Law paradigm and shows effects only if S-R compatibility is moderate or poor.

Guided eye movements and aimed pointing movements have high S-R compatibility.

Therefore, evidence for motor feature programming for these movements is actually weak or ambiguous.

No justification for maintaining motor feature programming if it interferes with model fitting.

- Need to make this decision in order to model high-performance realistically complex tasks.

Motor Features in Other Manual Movements?

What about other manual movements, such as key-pressing - are there still motor feature programming effects there?

Not clear yet - have to reassess the literature.

E.g. Choice-reaction task:

Subject presses keys in response to e.g. visual stimuli.
One key under each finger (Index, Middle, Ring, Little).
Nominally, seems to be one rule per S-R pair, so normal assumption is that specific S-R pairs are irrelevant; average them all together to get:

- Mean RT as a function of stimulus-response characteristics.
  E.g. Hick's Law, S-R compatibility.
- Learning curves.
  E.g. Power Law of Learning.

But we found powerful spatial-based nonhomogeneity in learning individual S-R pairs.

Lacey, et al., Psychonomics, 2004.
“Outer” keys are favored strongly over “inner” keys.

- Keys under the index and little fingers.

A strong interaction with S-R compatibility and learning rates as well.

Obscure, but good, precedents in the literature for our results.

Why were they ignored?

Golden Oldies: S-R Pair Spatial Effects

Alegria & Bertelson (1970)

Digit - key compatible mapping, index and little fingers over “outer” keys.
For 8 choice task, index and little fingers about 100 ms faster than others (about 500 vs 600 ms).
For 4 choice task, about 50 ms difference.

Welford (1971)

Row-of-lights to row-of-keys compatible mapping.
Similar 100 ms advantage of index and little fingers in 8 choice tasks.

- Similar reduced effects if fewer choices.
- Not biomechanical, not due to stimulus discriminability, but rather ease of identifying spatial position on "outside" of button group.

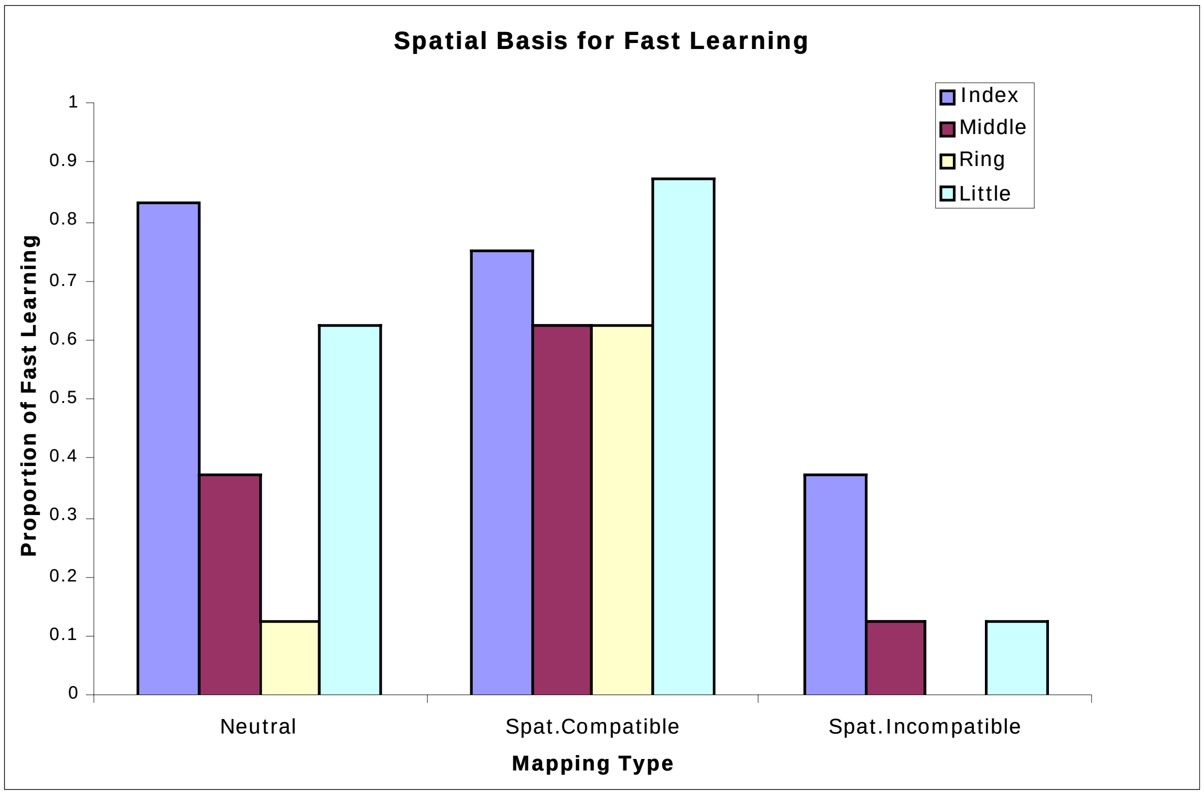
Welford concludes that response localization required:

"... choice reactions do not involve a perceptual-response task so much as a double perceptual task: first to identify the signal and then to identify the position in which a response should be made."

Our Results on Fast Learning of Individual S-R Pairs

Identify S-R pairs that show fast learning in different mappings:
Neutral, spatially compatible, spatially incompatible.
- Neutral is arbitrary - e.g. colors to keys.

"Outer" responses are often learned almost instantly.
Less if mapping is spatially incompatible.
All positions easier if spatially compatible mapping.



What is Learned in a Simple Choice Task?

Hypothetical processes in key-press choice reaction task:

Not:
Single production rule maps from the stimulus to the response finger, motor processor programs movement features.

Instead:
Possibly multiple production rules map from the stimulus to the response key *location*; motor processor quickly programs a move at that location.

Mappings to "outer" locations are faster learned and executed.
Still not clear why, but effects are too strong to ignore.
Fewer production rules involved in the mapping?

Conclusion: Spatial location is important even in key-press tasks.
Have to re-assess motor control literature to see if there are non-spatial forms of motor feature programming.

Changes to EPIC Motor Processors

Current workaround is simple:

Set feature programming time parameter to zero for saccades and aimed manual movements.

Will be made permanent if conclusions still hold after further review.

Effect on previous models:

Movement preparation relevant only if it was on the critical path.

- Some models overlapped preparation with other processes.

If on the critical path, motor preparation time was substituting for some of the response selection time.

- Our claims about simultaneous response selection in dual tasks are actually *stronger* with this revision.

Conclusions

Hypothesis: Primacy of Spatiality in Perceptual-Motor Relations

Nuggets of Gold

Lumps of Coal

Hypothesis: Primacy of Spatiality in Perceptual-Motor Relations

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Perceptual and motors processors can work directly in terms of spatial locations of objects.

Perceptual system collects and maintains spatial representation of objects.

- Note: Audition also has spatial information that specify eye movements.

When cognitive processor specifies target object to motor processor, motor processor initiates a movement to that location very rapidly.

Apparently, there is a subsystem that transforms visual coordinates to motor movements subcognitively and rapidly.

- Evidence that some brain areas do this, e.g. posterior parietal cortex.
- What is the representation and how does it work?

Why are spatially-compatible tasks so much easier than other tasks?

Maybe the question should be:

- Why are other tasks so much harder than spatially-compatible ones?

Perhaps spatial compatibility is the "normal"or natural mode of operation for the perceptual-motor system; everything else is a kludge.

We are biologically equipped by evolution to operate physically on objects located in the environment, not to make arbitrary movements in response to arbitrary events - we can do it, but it is convoluted and clumsy.

Nuggets of Gold

Architecture is definitely testable!
Could not fit reasonably without changes - always reassuring!

Closer to a usefully accurate model of visual system and how it is used in realistic tasks involving visual search.
Several important phenomena revealed and included in the model.

Central role of spatial effects in perceptual-motor performance:
Can't be ignored!
Trumps movement features, homogeneity assumptions in learning.
Spatial compatibility might be "normal" case, not the special case.
Need to study how non-spatial behaviors are represented that makes them harder to learn and execute.

Lumps of Coal

Various loose ends in models of visual search.

E.g. "objecthood" property - visual availability?

Identifying primacy of spatiality is just a start, not a conclusion!

Replace a simple movement feature analysis with a pervasive powerful spatial system of unknown properties - this is progress?

- What is it and how does it work?

We thought we knew the basis for most learned behavior - now it is just an ugly kludge?

Trashing conventional wisdom means empirical psychological literature is harder to use - hardly reassuring!

Can't accept conclusions of experimenters; must be an informed critic!