Working memory after 40 years

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Conference on WM and children’s learning Copenhagen 2014
Modal Model of Memory

Atkinson & Shiffrin (1971)

But, some problems.......e.g. “STM patients”
Baddeley & Hitch (1974)

Is STM important?
Does it act as a working memory?
Baddeley & Hitch (1974)

Is STM important?
Does it act as a working memory?

Approach:
- Use students to simulate neuropsychological patients
- Load STM with irrelevant material
- Examine effect on reasoning, comprehension, learning
Baddeley & Hitch (1974)

Is STM important?
Does it act as a working memory?

Approach:
Use students to simulate neuropsychological patients
Load STM with irrelevant material
Examine effect on reasoning, comprehension, learning

Results:
Consistent pattern of interference as irrelevant STM load was increased
Up to 3 items – little effect
6 items - effect
Multi-component model of working memory

Visuo-spatial Sketch Pad

Central Executive

Phonological Loop

Baddeley & Hitch, 1974; Baddeley, 1986
Separate lines of evidence converging on multi-component model

Tasks measuring distinct capacities
Patterns of:
  dual-task interference
  individual differences
  developmental differences
Selective impairments
Separate neural bases
Measuring capacities: Phonological loop

Digit span, letter span, word span

Nonword repetition span
  e.g. skiticult, blonterstaping, voltularity
  (Gathercole & Baddeley, 1996)
Measuring capacities: Visuo-spatial sketchpad

- Pattern span (visual)

Wilson, Scott & Power (1987)
Measuring capacities: Visuo-spatial sketchpad

- Corsi block span (spatial)
Measuring capacities: complex span

capacity to hold information in mind whilst performing mental operations

In terms of model: central executive + phonological loop (or VSSP)

Examples

   Reading span (Daneman & Carpenter, 1980)
   Listening span
   Counting span (Case et al., 1982)
   Operation span (Turner & Engle, 1989)
Complex span example: ‘Operation Span’

Hitch, Towse & Hutton (2001)
Individual differences: complex span and simple word span as predictors of verbal comprehension

Correlations (Daneman & Carpenter, 1980)

<table>
<thead>
<tr>
<th></th>
<th>Fact questions</th>
<th>Pronoun questions</th>
<th>Verbal SAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reading span</td>
<td>.72</td>
<td>.90</td>
<td>.59</td>
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<tr>
<td>Word span</td>
<td>.37</td>
<td>.33</td>
<td>.35</td>
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</tbody>
</table>
## Selective dual task interference

<table>
<thead>
<tr>
<th>Task</th>
<th>Subsystem disrupted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Articulatory suppression</td>
<td>Phonological loop</td>
</tr>
<tr>
<td>Spatial tracking</td>
<td>Visuo-spatial sketchpad</td>
</tr>
<tr>
<td>Counting backwards, random generation</td>
<td>Central executive plus phonological loop</td>
</tr>
</tbody>
</table>
Individual differences: Factor analysis of WM tasks

Children aged 6 - 15 given multiple assessments of

**Phonological loop:**
- digit span, word span, nonword span

**Visuospatial sketchpad:**
- pattern span, block recall, maze memory

**Central executive:**
- listening span, counting span, backwards digit span

Same 3-factor model gave a good fit across all ages

Gathercole, Pickering, Ambridge & Wearing, 2004
Developmental differences: immediate recall of names of pictured objects

Selective neuropsychological impairment of phonological loop

Patient PV

Normal:
Long-term memory
Intelligence
Language comprehension
Language production

Impaired:
Verbal STM
  auditory digit span = 2 items

Vallar & Baddeley
Tentative mapping of neuroimaging data

CE = Central executive
PS=phonological store
AR=articulatory rehearsal
VC = Visual Cache
IS=Inner Scribe

Henson, 2001
Summary of evidence converging on multi-component model

Tasks measuring distinct capacities

Patterns of:
  - dual-task interference
  - individual differences
  - developmental differences

Selective impairments

Separate neural bases
Phonological Loop

Distinct subsystem
  unique capacity
  selective interference
  selective impairment

Major functions
  inner speech
  vocabulary acquisition

Simple concept of loop needs augmenting
  serial order
  interface with LTM
Phonological loop as a language learning device

(Baddeley, Gathercole & Papagno, 1998)

Nonword repetition ability and digit span predict vocabulary scores in children

e.g. partial correlations between NWRep and BPVS vocabulary scores in 5-year-old children (N = 65)

\[ r = 0.48 \] (controlling for age, non-verbal IQ)
\[ r = 0.42 \] (controlling for digit span too)

Gathercole, Hitch, Service & Martin
Patient PV: Long-term learning of novel words

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Graph showing the learning of novel words over trials. The graph depicts the progress of learning words such as CASTLE and TABLE, as well as Russian words like FLOWER and SVIETI.
Nonword repetition in Specific Language Impairment

Gathercole & Baddeley (1990)
Phonological Loop and Serial order

Lashley (1951)

feature of many domains of behaviour

not chaining

simultaneously activated elements of sequence with repeated selection for output

rhythmic patterns of neural activity plus order schemata?
General form of cueing models

Serial order cues

Competition Between Items Active In Parallel

inhibition of selected item
Computational model of phonological loop

Two main components:

- Positional coding of serial order of items
- Phoneme-item loop

Modifiable connections decay
- Fast and slow weights (slow weights => learning)
Response of a population of detectors with different tunings (from 0.1 – 1.28 Hz) for ungrouped, regularly grouped (3-3-3) and irregularly grouped (2-6-1) sequences

Hartley, Hurlstone & Hitch, submitted
Model simulations vs overall percent correct for different grouping patterns

Hartley, Hurlstone & Hitch, submitted
Phonological Loop: Summary

Distinct subsystem
  unique capacity
  selective interference
  selective impairment

Major functions
  inner speech
  vocabulary acquisition

Simple concept of loop needs augmenting
  serial order
  interface with LTM

Dyslexia
  Serial order deficit (Majerus et al)
  Timing deficit (Goswami et al)
Questions for 3-component model:

Where is information in complex span tasks such as reading span stored?

How does long-term memory contribute to performance in WM tasks?

How is storage in visual and phonological buffers coordinated?
Episodic Buffer

Executive back-up store
- holds information directly available to central executive

Multimodal
- Integrates information from different sources (VSSP, PL, LTM)
- Binding

Limited capacity
- Chunking

Baddeley (2000)
Revised Multi-component Model

Baddeley (2000)
Using the change detection task to compare memory for individual features and bindings
Wheeler & Treisman (2002)

Single-item vs whole-display test
Binding memory suffers disproportionately with whole-display test

Baddeley, Allen & Hitch (2011)

Demanding concurrent task disrupts memory for features and bindings equally
Effects of concurrent backward counting on memory

Allen, Baddeley & Hitch (JEP: Gen, 2006)
Exploring the Episodic Buffer Binding across modality: e.g. colour auditory, shape visual

Memory for cross-modal vs unimodal feature bindings when performing an attention-demanding task at the same time

Allen, Hitch & Baddeley, Vis Cog (2009)
Modified Model – with binding automatic
Role of executive attention - effect of concurrent backward counting on memory for a series of coloured shapes

Memory for most recent item not dependent on executive attention

Allen, Baddeley & Hitch (in press)
Role of perceptual selective attention - effect of a to-be-ignored suffix on memory for a series of coloured shapes
Effect of a to-be-ignored suffix on memory for colour-shape bindings

Hu, Hitch, Baddeley, Zhang & Allen (submitted)
Pattern of recall and suffix effects depends on priorities given to different items

Attend recent

Attend early (primacy)

Recency

Primacy

Hu, Hitch, Baddeley, Zhang & Allen (submitted)
Episodic buffer: Summary

Holds bound multi-modal representations in a privileged state

Not involved in the process of binding

Privileged state
  highly accessible but highly labile
  vulnerable to overwriting
  limited capacity (2 or 3 items)
  “focus of attention”
  contents determined by interaction of:
    perceptual selective attention
    executive attentional control
Figure 1
A schematic overview of external and internal attention. Each box represents a target of attention.

Chun, Golomb & Turk-Browne (2011)
Cowan’s model of working memory
Practical applications
Characteristics of children with poor working memory

Poor academic progress
Difficulties in following instructions
Place-keeping difficulties
Teachers say short attention span and high distractibility

“he’s in a world of his own”
“she’s always day-dreaming”

Gathercole & Alloway (2008)
Why do these children struggle to learn?

• Learning is a step-by-step process, based on successes in individual learning activities.

• Children with working memory impairments often fail in the classroom because the working memory loads are excessive for them.

• Working memory failure leads to inattentive behaviour, simply because the child forgets what s/he is doing.
Can working memory deficits be overcome?
Working memory training

Commercial systems (e.g. CogMed, Klingberg et al 2005)

Game-style environment designed to train working memory using high-quality graphics game-style environment

Training on working memory tasks for 25 days over a 6-week period

Adaptive: individual works at span level
Training children with poor working memory

Holmes, Gathercole, & Dunning (2009)

Adaptive training: N = 22 10 year old children with poor verbal WM scores (<15th centile on each of 2 tests)

Non-adaptive training: 20 children with poor verbal WM scores

Pre- and post-training assessments
Working memory (AWMA), IQ (WASI), Maths, Reading
Gains in WM skills with adaptive vs non-adaptive training in children with low WM

Holmes, Gathercole, & Dunning (2009)
### IQ, Reading, Maths after adaptive WM training

<table>
<thead>
<tr>
<th>Time of testing:</th>
<th>Pre-training</th>
<th>Post-training</th>
<th>6mth follow-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measure</td>
<td>M</td>
<td>SD</td>
<td>M</td>
</tr>
<tr>
<td>Verbal IQ</td>
<td>88.73</td>
<td>11.14</td>
<td>90.86</td>
</tr>
<tr>
<td>Performance IQ</td>
<td>88.05</td>
<td>13.09</td>
<td>90.68</td>
</tr>
<tr>
<td>Reading</td>
<td>83.68</td>
<td>12.35</td>
<td>83.00</td>
</tr>
<tr>
<td>Mathematics</td>
<td>84.27</td>
<td>12.28</td>
<td>85.68</td>
</tr>
</tbody>
</table>

*Significant difference at p < .05

_Holmes, Gathercole, & Dunning_
Reviews of working memory training studies

Little evidence for ‘far’ transfer

Meta-analysis

Reliable short-term improvements in WM skills
Limited evidence of sustained improvement in WM skills
No reliable improvements in reading, arithmetic, attention

Engle et al, 2011

Melby-Lervag & Hulme, 2013
Classroom-based support

Reduce WM load of classroom activities

- task design
  - external storage
  - errorless learning
- chunking
- instructions
## Mental arithmetic

<table>
<thead>
<tr>
<th>Sum complexity</th>
<th>Easy</th>
<th>Hard</th>
<th>Carry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>8 + 1</td>
<td>3 + 5</td>
<td>5 + 9</td>
</tr>
<tr>
<td>Level 2</td>
<td>21 + 7</td>
<td>22 + 6</td>
<td>23 + 9</td>
</tr>
<tr>
<td>Level 3</td>
<td>122 + 3</td>
<td>123 + 4</td>
<td>127 + 4</td>
</tr>
<tr>
<td>Level 4</td>
<td>31 + 26</td>
<td>76 + 23</td>
<td>51 + 66</td>
</tr>
<tr>
<td>Level 5</td>
<td>231 + 16</td>
<td>233 + 45</td>
<td>296 + 21</td>
</tr>
<tr>
<td>Level 6</td>
<td>611 + 136</td>
<td>574 + 422</td>
<td>628 + 931</td>
</tr>
<tr>
<td>Level 7</td>
<td>2412 + 123</td>
<td>2242 + 527</td>
<td>2834 + 624</td>
</tr>
<tr>
<td>Level 8</td>
<td>4813 + 1152</td>
<td>3623 + 5356</td>
<td>1512 + 5842</td>
</tr>
</tbody>
</table>

Adams & Hitch, 1997
Mental addition improved by external storage

Adams & Hitch, 1997
## Errorless learning

<table>
<thead>
<tr>
<th>Errorful</th>
<th>Errorless</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial &amp; error</td>
<td>“...the elimination .. of incorrect ..responses during training...” (Clare et al., 2000)</td>
</tr>
<tr>
<td>Errors learned &amp; compete with correct answer</td>
<td>Reduces competition between error &amp; correct target</td>
</tr>
<tr>
<td>Places load on working memory</td>
<td>Reduces load on working memory</td>
</tr>
</tbody>
</table>
Comparison between errorful and errorless methods

Procedure

Adapted from Baddeley & Wilson (1994)
Learn unfamiliar names for a set of unfamiliar objects

Errorful:

This object’s name begins with the letter P. Can you guess it’s name?
Corrective feedback provided

Errorless:

This object’s name begins with the letter P; it’s a prot. Can you say prot?

Training across 4 trials

Warmington, Hitch & Gathercole (2013)
Improving word learning in children using an errorless technique

Warmington, Hitch & Gathercole (2013)
Learning unfamiliar old English words and their definitions

Errorless:

e.g. A course dark sugar is called jaggery.

What is the name for a coarse dark sugar? (response)

Errorful:

e.g. What is the name for a coarse dark sugar? (response)
A coarse dark sugar is called jaggery (+ expanding intervals)

Warmington & Hitch, 2013
Effect of learning method on dyslexic adults' acquisition and retention of novel object names

Warmington & Hitch (in preparation)
Errorless learning summary

New words
  Children and adults
  Semantic and non-semantic
  Dyslexic adults
  Working memory?

Spelling?

Arithmetic number bonds?
Forty years of working memory

Simple, broad, usable theory

links widely different sources of evidence
developed slowly in light of evidence
  new: episodic buffer and focus of attention
  interaction between executive control & perceptual selective attention

Reliable measures, robust methods, useful tools

Simple model helps organise what we know and what questions we still need to answer

Widely applicable to practical problems
Thanks for listening
and acknowledgements to
many, many collaborators over the years and
most especially my mentor and colleague, Alan Baddeley

The End
Mean scores on listening span test from WMTB-C* as a function of age, with 10th & 90th centiles

*Working Memory Test Battery for Children, Pickering & Gathercole (2001)
Mean scores on listening span test from WMTB-C* as a function of age, with 10th & 90th centiles
Characteristics of children with poor working memory
Characteristics of children with poor working memory

• Poor academic progress

More than 80% of children with poor working memory fail to achieve expected levels of attainment in either reading or maths, typically both (Gathercole & Alloway, 2008)
Characteristics of children with poor working memory

- Poor academic progress
- Difficulties following instructions

“Put your sheets on the green table, arrow cards in the packet, put your pencil away and come and sit on the carpet.”

John (6 years) moved his sheets as requested, but failed to do anything else. When he realized that the rest of the class was seated on the carpet, he went and joined them, leaving his arrow cards and pencil on the table.
Characteristics of children with poor working memory

- Poor academic progress
- Difficulties in following instructions
- Place-keeping difficulties

*When the teacher wrote on the board Monday 11th November and, underneath, *The Market*, which was the title of the piece of work, Nathan lost his place in the laborious attempt to copy the words down letter by letter, writing moNemarket.*
Characteristics of children with poor working memory

- Poor academic progress
- Difficulties in following instructions
- Place-keeping difficulties
- Teachers say short attention span and high distractibility

“he’s in a world of his own”
“she’s always day-dreaming”
Working memory: in summary

- Multi-component system
- Limited capacity
- Measurable
- Large individual differences in the normal population
- Supports many aspects of cognition and learning
- Deficits in WM linked to a range of learning disabilities, general and specific
Down and Williams syndromes

**Observed**

**MA adjusted**

Jarrold, Baddeley & Hewes (1999)
Working memory and arithmetical learning difficulties

McLean & Hitch, 1999
9 year olds

<table>
<thead>
<tr>
<th></th>
<th>Poor arithmetic</th>
<th>Age controls</th>
<th>Arithmetic ability controls</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N=12</td>
<td>N=12</td>
<td>N=12</td>
</tr>
<tr>
<td>Digit span</td>
<td>4.8 (0.5)</td>
<td>5.4 (0.8)</td>
<td>4.8 (0.9)</td>
</tr>
<tr>
<td>Nonword repetition</td>
<td>26.2 (6.0)</td>
<td>26.2 (4.9)</td>
<td>26.9 (6.4)</td>
</tr>
<tr>
<td>Matrix span</td>
<td>7.8 (2.9)</td>
<td>7.3 (2.0)</td>
<td>6.4 (1.8)</td>
</tr>
<tr>
<td>Corsi span</td>
<td>3.9 (0.6)</td>
<td>4.9 (0.7)</td>
<td>*** 4.0 (0.8)</td>
</tr>
<tr>
<td>Trails Written</td>
<td>75.1 (16.1)</td>
<td>53.9 (12.5)</td>
<td>* 78.5 (31.2)</td>
</tr>
<tr>
<td>Trails Verbal</td>
<td>66.8 (26.3)</td>
<td>38.9 (13.9)</td>
<td>** 61.3 (30.2)</td>
</tr>
<tr>
<td>Trails Color</td>
<td>52.2 (13.3)</td>
<td>33.4 (11.5)</td>
<td>** 49.2 (13.6)</td>
</tr>
</tbody>
</table>

See also Passolunghi & Mammarella, 2010