How conscious experience and working memory interact

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Active components of classical working memory are conscious, but traditional theory does not account for this fact. Global Workspace theory suggests that consciousness is needed to recruit unconscious specialized networks that carry out detailed working memory functions. The IDA model provides a fine-grained analysis of this process, specifically of two classical working-memory tasks, verbal rehearsal and the utilization of a visual image. In the process, new light is shed on the interactions between conscious and unconscious aspects of working memory.

All active components of cognitive working memory (WM) are accurately reportable: for example, perceptual input, rehearsal, recall, and the act of responding with a recalled item. But accurate report is also the standard operational index of consciousness [1]. Could that be a coincidence, or are conscious contents needed for WM? Several theorists now suggest an active role for conscious events in working memory [1–6].

Global Workspace theory (GW) suggests that conscious experiences involve widespread distribution of focal information, to recruit neuronal resources for problem solving [1,2,7,8]. Brain studies suggest that the sensory and frontolimbic cortices could serve such a distributive/integrative function, consistent with their thalamocortical connectivities [2,9–11]. Such dynamics have been observed via implanted electrodes in the human brain during working-memory tasks [12].

Previous expositions of these points have been general in nature. It makes sense therefore to explore them with a detailed implementation of the theory.

Using IDA (Intelligent Distribution Agent), a large-scale model of Global Workspace theory [13,14], we show how the conscious components of working memory can help mobilize and guide unconscious routines that carry out WM functions. The IDA model can elucidate these functions, as well as executive control of working memory. This provides a functioning model of how conscious events may help to accomplish cognitive tasks [2].

Working memory

Baddeley and Hitch's working memory model is probably the most influential integrative model of cognition of the last few decades [15,16] (see Fig. 1). Its basic constructs are easily testable, including the phonological buffer (tested by silent rehearsal of numbers or words), the visuospatial sketchpad (using mental images in problem solving), and the central executive (shown by voluntary manipulations of WM functions). The brain basis of these functions is increasingly well understood.

Fig. 1 notes that many WM functions have conscious aspects, either 'qualitative' ones such as inner speech or visual imagery, or 'fringe conscious' experiences, like the intention to recall and report WM items. Both can be assessed by accurate report.

Global Workspace theory

Global Workspace theory is a cognitive architecture with an explicit role for consciousness (Fig. 2). It makes minimal assumptions:

(1) that the brain can be viewed as a collection of distributed specialized networks (processors);
(2) that consciousness is associated with a global workspace in the brain – a fleeting memory capacity whose focal contents are widely distributed ('broadcast') to many unconscious specialized networks;
(3) conversely, a global workspace can also serve to integrate many competing and cooperating input networks;

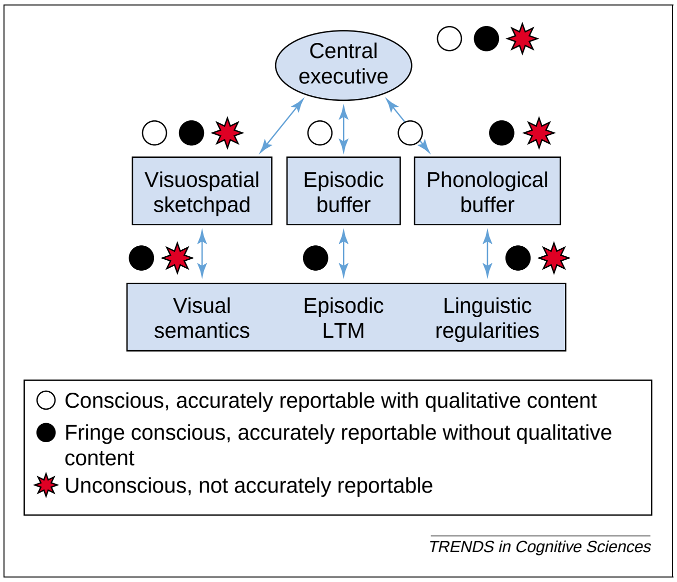

Fig. 1. A model of working memory. (Modified after [6]. See text for explanation of terms.)

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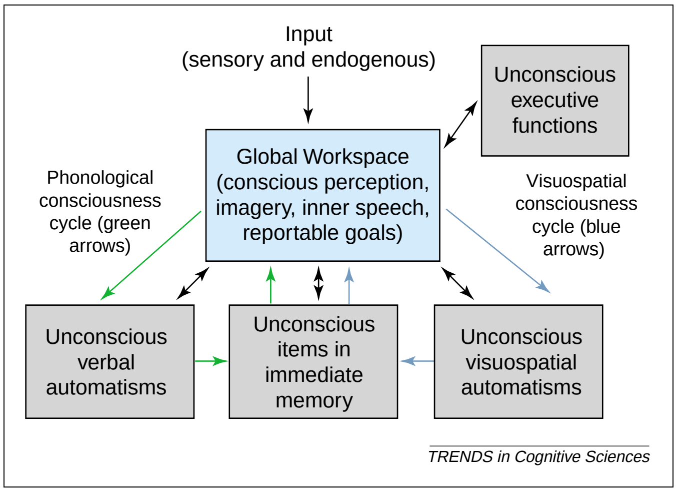

Fig. 2. Conscious elements play an essential role in distributed working memory functions. Phonological (green arrows) and visuospatial (blue arrows) consciousness cycles are highlighted.

(4) that some unconscious networks, called contexts, shape conscious contents. (For example, unconscious parietal maps modulate visual feature cells that underlie the perception of color in the ventral stream.);
(5) that such contexts work together jointly to constrain conscious events;
(6) that motives and emotions can be viewed as goal contexts;
(7) that executive functions work as hierarchies of goal contexts.

Several of these functions have plausible brain correlates, and the theory has recently aroused considerable interest in cognitive neuroscience and philosophy [2,17].

Figure 2 shows how a global workspace capacity associated with consciousness might recruit typical working memory functions like mental rehearsal and visual imagery. These are traditionally considered 'slave systems' in WM theory, and are believed to operate as partly autonomous distributed networks, as also suggested in Global Workspace (GW) theory. They are guided by executive functions, which are viewed as goal hierarchies in GW theory.

The IDA implementation of GW theory

IDA (Intelligent Distribution Agent) is an autonomous software agent [18] that automates the entire set of tasks of a human personnel agent who assigns sailors to new tours of duty [19]. This includes constraint satisfaction, temporal deliberation, voluntary action selection, and negotiating with the sailor in natural language. The IDA model fleshes out GW theory so as to yield a fine-grained functional account of the steps involved in perception, several kinds of memory, consciousness, context setting, and action selection. We refer to this sequence as the cognitive cycle and describe it in detail in the next section. In addition to GW theory, IDA models a broad swath of cognition (see Table 1).

We propose a close relationship between classical working memory functions, Global Workspace theory, and its IDA model. Table 2 makes the proposed relationships explicit, and cites some related brain evidence. Note that the granularity of the models increases from Working Memory to Global Workspace theory, with the highest level of detail represented in the IDA model.

As a result of this more finely grained account than is typical in cognitive science, several of the names of IDA modules and processes have slightly different meanings than is customary. In particular, IDA's module labeled 'Perception' is entirely preconscious; it does not include consciousness awareness. IDA's 'working memory' module models only the preconscious buffers of cognitive working memory, the visuospatial sketchpad and the phonological loop. By contrast, the cognitive cycle as a whole also models the central executive as well as conscious functions. IDA's long-term associative memory includes semantic memory and long-term episodic memory. In addition, she has a transient episodic memory [20].

Processing in IDA consists of repeated journeys through the cognitive cycle described in the next section. More than one cognitive cycle can proceed at any given time, although they are funneled through a serial 'bottleneck' when they make use of IDA's global workspace capacity. This reflects the theoretical claim that consciousness imposes seriality on otherwise concurrent processes.

The roots of this idea go back to the 19th century, when writers like Francis Galton and William James observed that conscious contents seem to jump from one to the next, but also that they seem to be linked by associative themes that emerge many times. In GW–IDA terms, these themes are expressed in cognitive cycles that engage in problem-solving at many different levels of analysis, each one only momentarily dominating conscious contents (the global workspace). During conscious moments, seriality is

Table 1. IDA's modules, the sources of their mechanisms, and the theories they support

IDA module	Computational mechanism motivated by:	Theories accommodated
Perception	Copycat architecture [26]	Perceptual symbol systems [27]
Working memory		Working memory [16] Long-term working memory [28]
Emotions	Neural networks [29]	[30,31]
Associative memory	Sparse distributed memory [32]	
Episodic memory	Sparse distributed memory [32]	[20,33]
Consciousness	Pandemonium theory [34]	Global Workspace theory [35]
Action selection	Behavior nets [35]	Global Workspace theory [1]
Constraint satisfaction	Linear functional (standard operations research)	
Deliberation	Pandemonium theory [34]	Human-like agent architecture [36]
Voluntary action	Pandemonium theory [34]	Ideomotor theory [35,37]
Language generation	Pandemonium theory [34]	
Metacognition	Fuzzy classifiers [38]	Human-like agent architecture [36]

Table 2. Relationships between working memory theory, Global Workspace theory and IDA

Extended WM	GW theory	IDA model	Some plausible brain bases
Preconscious visuo-spatial and auditory-phonological analysis.	Unconscious input analysis.	Early preconscious perception	Early visual and auditory cortex
Preconscious identification of objects, words and other single chunks.		Late preconscious perception (using slipnet)	Visual/auditory object and word recognition areas of cortex, reentering widely via gamma coherence.
Perceptual input into WM storage.		Percept to preconscious buffers.	
		Local associations. (retrieved from transient episodic memory and long term memory).	
The following involve multiple GW and IDA cycles: instructions to rehearse. Rehearsal (retrieval, repetition/manipulation, and storage). Instructions to retrieve and report. Retrieval and report. (Instructed tasks are under the control of the Central Executive.)	For each conscious event: competition for global workspace until one input processor (or coalition) gains access and becomes conscious.	For each cognitive cycle that involves a conscious event: competition for consciousness. (attention codelets).	First stable re-entrant organization of perceptual and immediate association areas.
	Broadcast of conscious perceptual or internal contents, such as conscious images and inner speech.	Broadcast of conscious contents.	Correlated firing from sensory projection areas to target areas: parietal, frontolimbic and medial-temporal cortex, hippocampus and basal ganglia.
	Recruitment of resources (processors). Setting of goal context hierarchy.	Recruitment of resources (behavior codelets). Behavior stream.	Re-entry between target areas and sensory cortex. Frontolimbic re-entrant processing to prepare action.
	Action is chosen and prepared. Internal or external actions taken by specialized processors (networks).	Action chosen. Internal or external actions taken by behavior codelets (possibly writing to preconscious buffers).	Motor efference from motor/premotor cortex.

enforced because of the practical importance of maintaining the temporal order of events. When cognitive cycles are unconscious, however, parallelism prevails.

Though the IDA model seems modular (Fig. 3), much of that is an illusion. Almost all the work in the system is done by codelets, implementing the unconscious processors (specialized networks) of GW theory. A codelet is a small piece of code, a little program, that performs one specialized, simple task. Codelets often play the role of demons waiting for a particular type of situation to occur and then acting out their specialized roles. Codelets in the IDA model are implementations of the processors in Global Workspace theory. They might also corresponding to Edelman's neuronal groups [21], Minsky's agents [22] or to Ornstein's small minds [23]. Codelets come in several varieties; the function of each will be described as it appears.

IDA's cognitive cycle

Processing in IDA is, for the most part, a continuing iteration of a cycle of activities involving modules called Perception, working memory, episodic memory, long-term associative memory, consciousness, action selection and motor activity. (IDA's working memory module is not to be confused with the cognitive construct of working memory.) Called the cognitive cycle, it can be useful conceived of as a sequence of nine steps as described in detail in the text box.

Figure 3 gives an overview of the cognitive cycle. An example of IDA's finer-grained analysis is in Steps 1 and 2 of the cognitive cycle, which distinguish between the incoming preconscious percept and the preconscious buffer of working memory into which it is stored (see Box 1).

We hypothesize that a similar cycle underlies much of human cognition. Our picture is of cognition as a continuing stream of cognitive cycles, overlapping so as to act somewhat in parallel. Because any single cognitive cycle can only become conscious at any given instant, their parallelism is constrained in such as way as to maintain the seriality of consciousness. We conjecture that a full cognitive cycle might take a minimum of 200 ms. But because of overlapping and automaticity, which shortens the cycle (see below), as many as twenty cycles could be running per second. Working-memory tasks occur on the order of seconds, indicating that several cognitive cycles may be needed for any given WM task, especially if it has conscious components such as mental rehearsal.

Although we describe an iterating cycle from step 1 to step 9, in many tasks the cycle might begin with step 8, starting from an action that will enable some particular perception. That is because human beings are active, curious, and exploratory creatures, in which much input is interpreted in the context of ongoing activities. Cotterill refers to this as 'self-paced probing of the surroundings.' [24].

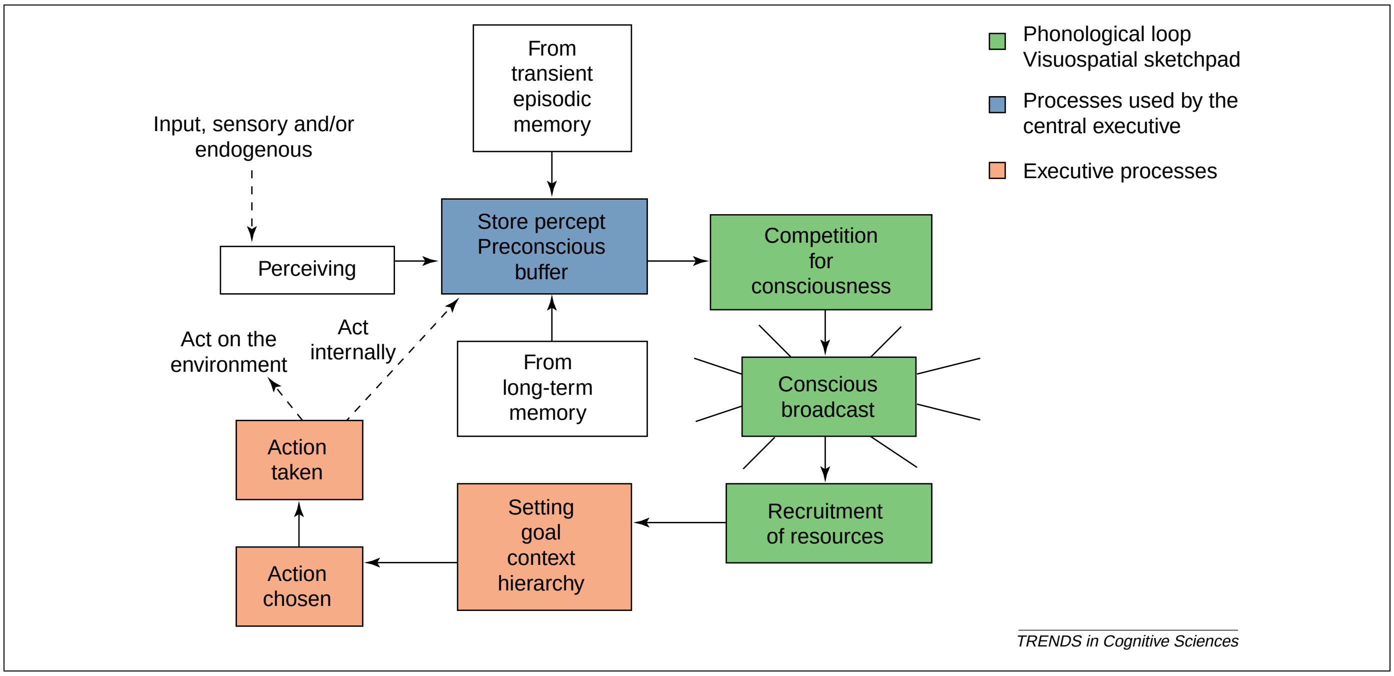

Fig. 3. The cognitive cycle, color coded for its relationship to working memory.

Steps 4–9 can be thought of as implementing the 'central executive' in Baddeley's working memory theory. Here the goals that will shape actions are recruited, organized and executed.

Highly practiced and therefore automatic sequences of actions correspond to unconscious specialized functions in GW theory. In these cases, steps 1 through 5 are omitted. Step 6, recruitment of resources, is brought about by IDA's currently active behavior codelets[1], which perform the current action, activate new behavior codelets to perform the next action via their strong associations. In this case the behavior stream[2] of step 7 is already in place with variables for the next behavior (action) already bound.[3]

In step 7 we assume the existence of such an appropriate behavior stream – that is, that the situation is basically known, with possibly novel specifics. If no such behavior stream exists, the non-routine problem-solving apparatus is called into play. The resulting process, perhaps requiring repeated trips through the cognitive cycle under the auspices of its own behavior stream, creates a new behavior stream capable of dealing with the novel or problematic situation. Such new behavior streams are learned.[4] In what follows, using iterated cognitive cycles, we produce a fine-grained analysis of two typical working-memory tasks, mentally rehearsing a number and solving a problem with a visual image.

Verbal rehearsal was extensively investigated for short-term memory tasks, and the first model of working memory was much influenced by this research tradition [15]. The use of mental imagery in problem-solving, or the 'visuospatial sketchpad' in WM terms, is equally vital. We model these two tasks in ways the reader can easily experience personally (see Boxes 2 and 3). We recommend paying careful attention to one's own experience of these tasks, in addition to the large number of objective studies available.

Note that in this analysis the subject becomes conscious of the response to the question only as a result of the verbal report. In a more complex situation, the subject could become conscious of the image before composing a verbal report. For example, in a situation in which the subject might not want to give a correct answer it would make sense to first bring the planned response to consciousness. This would require additional cognitive cycles implementing voluntary action selection [25], still well within the explanatory range of the model.

Relationships between the theories

Table 2 shows the relationships between working memory theory, Global Workspace theory, and IDA. It also suggests some brain mechanisms. We use the term 'extended working memory' to include standard WM plus widely accepted ideas like unconscious pre-perceptual analysis, unconscious automatic skill components, and the like. Whereas the IDA Model column describes a single cognitive cycle (see Box 1) the items in the WM column generally require repeated cognitive cycles.

Empirical predictions

The empirical point of departure for this article is the observation that the 'active' components of classical working memory depend upon accurate report by the subject. As accurate report is generally held to index conscious events, there is already a great body of reliable evidence that raises the question, 'How do conscious elements relate to traditional aspects of working memory?'

1 Codelets in IDA correspond to specialized processors (networks) in GW theory.
2 A behavior stream in IDA corresponds to a goal context hierarchy in GW theory.
3 Such automatic sequences are learned through repetition of the consciousness cycle. (The mechanism is described elsewhere.)
4 Cotterill refers to these as 'content-specific reflexes' [24] (This process is fully described elsewhere.)

Box 1. Steps in the cognitive cycle

(1) **Perception**
Sensory stimuli, external or internal, are received and interpreted by perception creating meaning. Note that this stage is unconscious.
Early perception. Input arrives through senses. Specialized perception codelets descend on the input. Those that find features relevant to their specialty activate appropriate nodes in the slipnet (a semantic net with activation).
Chunk perception. Activation passes from node to node in the slipnet. The slipnet stabilizes, bringing about the convergence of streams from different senses and chunking bits of meaning into larger chunks. These larger chunks, represented by meaning nodes in the slipnet, constitute the percept.

(2) **Percept to preconscious buffer**
The percept, including some of the data plus the meaning, is stored in preconscious buffers of IDA's working memory. These buffers might involve visuospatial, phonological, and other kinds of information.

(3) **Local Associations**
Using the incoming percept and the residual contents of the preconscious buffers as cues, local associations are automatically retrieved from transient episodic memory and from long-term associative memory. The contents of the preconscious buffers together with the retrieved local associations form transient episodic memory and long term associative memory. Together these roughly correspond to Ericsson and Kintsch's long-term working memory and Baddeley's episodic buffer.

(4) **Competition for consciousness**
Attention codelets, whose job it is to bring relevant, urgent, or insistent events to consciousness, view long-term working memory. Some of them gather information, form coalitions and actively compete for access to consciousness. The competition can also include attention codelets from a recent previous cycle.
The activation of unsuccessful attention codelets decays rapidly, making it more difficult for them to compete with newer arrivals. However, the contents of unsuccessful coalitions remain in the preconscious buffer and can serve to prime ambiguous future incoming percepts. The same is true of contents of long-term working memory that aren't picked up by any attention codelet.

(5) **Conscious broadcast**
A coalition of codelets, typically an attention codelet and its covey of related information codelets carrying content, gains access to the global workspace and has its contents broadcast. This broadcast is hypothesized to correspond to phenomenal consciousness.
The current contents of consciousness are also stored in transient episodic memory. At recurring times not part of a cognitive cycle, the contents of transient episodic memory are consolidated into long-term associative memory [33] Transient episodic memory is an associative memory with a moderately fast decay rate, on the order of hours [20]. It is to be distinguished from autobiographical memory, a part of long-term associative memory.

(6) **Recruitment of resources**
Relevant behavior codelets respond to the conscious broadcast. These are typically codelets whose variables can be bound from information in the conscious broadcast. If the successful attention codelet was an expectation codelet calling attention to an unexpected result from a previous action, the responding codelets may be those that can help to rectify the unexpected situation. Thus consciousness solves the relevancy problem in recruiting resources.

(7) **Setting goal context hierarchy**
Some responding behavior codelets instantiate an appropriate behavior stream, if a suitable one is not already in place. They also bind variables, and send activation to behaviors. Here we assume that there is such a behavior codelet and behavior stream. If not, then non-routine problem solving using additional mechanisms is called for (see below).

(8) **Action chosen**
The behavior net chooses a single behavior (goal context) and executes it. This choice might come from the just instantiated behavior stream or from a previously active stream. The choice is affected by internal motivation (activation from goals), by the current situation, external and internal conditions, by the relationship between the behaviors, and by the activation values of various behaviors.

(9) **Action taken**
The execution of a behavior (goal context) results in the behavior codelets performing their specialized tasks, which might have external or internal consequences. This is IDA taking an action. The acting codelets also include an expectation codelet (see step 6) whose task it is to monitor the action and to try and bring to consciousness any failure in the expected results.

In addition, the GW–IDA model should make novel predictions. In recent years much progress has been made in identifying 'regions of interest' in the brain that seem to be required for working memory functions. For example, vivid imagery appears to recruit visual cortex and WM rehearsal seems to involve Broca's and Wernicke's areas. Moreover, skills that become automatic with practice depend on the basal ganglia, using less cortical activity as they become less conscious. Thus some unconscious WM functions might be supported by basal ganglia. Effortful goal-directed WM functions, on the other hand, seem to require prefrontal and anterior cingulate cortex.

In principle, all features of the GW–IDA approach can be tested in this way. Because cognitive cycles are rather fast, brain scans with high temporal and spatial resolution are at a premium (see [12]).

Conclusions

Working memory is the most influential empirical model of cognitive functions to date, and the one with perhaps the greatest body of evidence. But it has some gaps. The role of conscious elements is not specified, and the granularity of the theory is relatively coarse. A key observation is that all active components of classical working memory are conscious: input, rehearsal, visuospatial operations, recall and report. This is easily shown by the fact that these events can be reported accurately, whereas the details of unconscious processes like memory search cannot. This fundamental fact suggests that conscious experiences play a key role in classical working memory.

Global Workspace theory suggests that conscious contents recruit widespread unconscious functions, via a broadcast of the contents. IDA specifies these functions in great detail, sufficient to carry out practical tasks in a complex real-world environment. IDA also suggests in great detail how classical working-memory tasks might be accomplished. The results seem broadly consistent with the brain mechanisms that are believed to carry out these functions.

Many more aspects of consciousness and cognition can

Box 2. Fine-grained analysis of rehearsal in working memory (phonological loop)

Situation: A subject is asked to remember a seven-digit telephone number for thirty seconds. The number is presented visually, together with the request to remember.

Assumption: The subject is prepared to comply with the instruction.

Analysis:

1. **Input.** (Cognitive Cycle (CC) steps 1 and 2). The input is sensed, recognized and stored as a percept in the pre-conscious buffers including sound, vision and meaning.
2. **Automatic local associations.** (CC step 3). Using the percept from step 1 as a cue, local associations are retrieved from episodic and long-term memory. In this case there might be nothing relevant, unless the telephone number was known or other input had occurred in the past.
3. **Consciousness.** (CC steps 4 and 5). An attention codelet, observing the preconscious buffer and the local associations, brings the sounds, visual images and their meaning to consciousness via a broadcast. At each broadcast the contents of consciousness are also stored in transient episodic memory.
4. **Task plan.** (CC steps 6 and 7). Behavior codelets respond to the conscious broadcast, instantiate an appropriate behavior stream for responding to the input, bind variables, and send activation to behaviors.
5. **Subject says 'yes' to the request.** (CC steps 8 and 9). A behavior (goal context) to respond to the experimenter is selected. Its underlying behavior codelets become active and produce a verbal assent. (This may require more than one behavior in the case of an automatic sequence.)
6. **Hearing and understanding 'yes'.** (CC steps 1 and 2). The spoken assent is sensed, understood, and stored as a percept, both sound and meaning, in the phonological loop of the preconscious buffer.
7. **Automatic associations.** (CC step 3). Using this percept as a cue, local associations are retrieved from episodic and long-term memory. In this case there is perhaps nothing of relevance other than the remembered telephone number.
8. **Conscious rehearsal.** (CC steps 4 and 5). An attention codelet, observing the preconscious buffer and the local association of the number from transient episodic memory, brings the sound of the assent and its meaning to consciousness via a broadcast along with an image of the telephone number. The contents are stored in episodic memory.
9. **Rehearsal plan.** (CC steps 6 and 7). Behavior codelets respond to the conscious broadcast, instantiate an appropriate behavior stream for rehearsal, bind variables, and send activation to behaviors.
10. **Unconscious inner speech.** (CC steps 8 and 9). A behavior (goal context) to rehearse the telephone number is selected. Its underlying behavior codelets become active and produce an internal verbal image of the telephone number.
11. **Unconsciousness inner speech perception.** (CC steps 1 and 2). This inner voice version of the telephone number is sensed, understood, and stored as a percept, both sound and meaning, this time in the phonological loop portion of the preconscious buffer.
12. **Local automatic associations.** (CC step 3). Using this percept as a cue, associations are retrieved from transient episodic and long-term memory. In this case there might be nothing relevant other than the remembered telephone number.
13. **Consciousness of inner speech.** (CC step 4 and 5). An attention codelet, observing the preconscious buffer and the local associations, brings the internal sound of the telephone number and its meaning to consciousness via a broadcast. Its contents are stored again in transient episodic memory.
14. **Rehearsal plan continued.** (CC steps 6 and 7). Behavior codelets respond to the conscious broadcast and, using the behavior stream for remembering the telephone number, bind variables, and send activation to behaviors.
15. **Unconsciousness inner speech.** (CC steps 8 and 9). A behavior to rehearse the telephone number is selected. Its underlying behavior codelets become active and produce an internal verbal image of the telephone number.
16. **Repeat until overt response.** (CC steps 1–9 iterated.) The process is repeated for thirty seconds. At that time a slightly different behavior in the same behavior stream is selected, whose underlying codelets become active and produce an overt verbal expression of the telephone number.

Box 3. Analysis of the visuospatial sketchpad of working memory

Situation: The subject is asked verbally to visualize his front door and to tell whether the doorknob is on the left or the right.

Assumption: The subject is prepared to comply with instructions.

Analysis:

1. **Input**. (CC steps 1 and 2). The input is sensed, understood, and stored as a percept, both sound and meaning, in the preconscious buffer.
2. **Automatic local associations**. (CC step 3). Using the percept as a cue, local associations are retrieved from transient episodic and long-term memory. In this case one of the associations is a visual image of the front door, which is stored in the visual sketchpad portion of the preconscious buffer.
3. **Consciousness**. (CC steps 4 and 5). An attention codelet, observing the preconscious buffer, brings the sounds and their meaning to consciousness via a broadcast, along with the visual image of the front door.
4. **Task plan**. (CC steps 6 and 7). Behavior codelets respond to the conscious broadcast, instantiate a behavior stream that allows for both searching the image and producing a response, bind variables, and sends activation to behaviors (goal contexts).
5. **Forming the image**. (CC steps 8, 9, 1 and 2). A behavior to focus on the doorknob is selected. Its underlying behavior codelets become active, cause visual focusing on the doorknob in the image of the door, note its position, and store all this in the preconscious buffer.
6. **The conscious visual image**. (CC steps 3, 4 and 5). An attention codelet, observing the preconscious buffers and their local associations, brings the image and related information to consciousness via a broadcast.
7. **Resources recruited**. (CC steps 6 and 7). Behavior codelets respond to the conscious broadcast, bind variables and send activation to behaviors in the existing behavior stream.
8. **Overt verbal report**. (CC steps 8 and 9). A behavior (goal context) to compose a response to the experimenter is selected. Its underlying behavior codelets become active, and compose an appropriate verbal response using the phonological preconscious buffer. Others of these active behavior codelets carry out the spoken response. (This may require more than one behavior in an automatized unconscious sequence.)
9. **Sensing the response**. (CC steps 1 and 2). The verbal response is sensed, understood, and stored as a percept, both sound and meaning, in the preconscious buffer.
10. **Subject's response becomes conscious**. (CC steps 3, 4 and 5). Using this percept as a cue, local associations are retrieved from transient episodic and long-term memory. An attention codelet, observing the preconscious buffers and the local associations, brings the sounds and their meaning to consciousness via a broadcast.

be modeled with this approach, yielding explicit, testable and detailed predictions.

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