External Working Memory and the Amount of Distributed Cognition

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Abstract

While processing of a large number of (visuo-spatial) items are oftentimes necessary for ongoing cognitive activities, the biological working memory can process only about four items of information. Then it is a mystery how we cope with complex world situations. This is the paradox of working memory. This paradox is solved once we view the external features of the world as constituting part of working memory. Part of working memory is externally distributed if the external features of the world constitute part of material supervenience base of working memory. Tversky's Spractions (2010), or actions onto the world, are the key to offload of cognition, because they redirect the attention at the working memory level only to relevant aspects of the world. To see how people use spractions to offload working memory load, subjects were asked to build a Lego block in front of a camera. Using cognitive ethnography, it was observed that they all relied on spractions to cognize. From the fact that the biological working memory can process only about four items of information, the amount of working memory based distributed cognition can be calculated.

Keywords: paradox of working memory; external working memory; spractions

Introduction

Working memory (hereafter WM) is a limited capacity system to temporarily maintain, access, and update information necessary for ongoing cognitive activities (Baddeley, 2000, 2003; Awh et al., 2006; Jonides et al, 2008). Traditionally it is conceived of as short-term memory (STM) buffer, characterized by the firing of neurons; it can hold information for a couple of seconds. Since STM does not involve structural change of neural networks, information stored in STM is transient. STM, and hence WM, is one of the core components of cognition. Hardly any cognitive task can be completed without the involvement of STM. For example, when you add some numbers, you have to create a temporal mental representation for those numbers. Biological WM is a limited capacity system; it can maintain, access, and update only limited amount of information simultaneously. In his seminal paper "*The magical number seven, plus or minus two,*" George Miller (1956) argued that the capacity of WM is limited to about seven items of information. However, as later pointed out, Miller's magical number seven was inflated due to the confound effect of linguistic chunking, a strategy to group small items of information into an integrated representation (discussed more below). According to a more accurate estimate (Sperling, 1960; Landman et al., 2003; Cowan, 2001; Jonides et al., 2008; Hauser et al., 2000; Block, 2007), the capacity of biological (visuo-spatial) WM of human adults is limited to about four items of information. That is, WM can selectively attend to only about four items of information simultaneously.

While the capacity of biological WM is limited to about four items of information, the world around us is full of complexity, rich in detail, and oftentimes cluttered (i.e. there are usually more than four items of information in the world, and they are oftentimes relevant to ongoing cognitive activities). Thus, there is an overflow of information at the WM level (Kessell and Tversky, 2010; c.f. Rowlands, 1999; Block, 2007, 2011). Although we have to cognize quickly in response to stimuli in the world to survive (c.f. Cruse, 2003; Kirsh and Maglio, 1994), given the complexity of the world and the limited WM capacity, it is not at all clear how we can do so. Nevertheless, we are almost entirely unaware of the limitation of biological WM in daily life except for some minor occasions such as remembering a telephone number for the first time, and cope with high cognitive tasks day by day. It is a mystery how a severely constrained WM can cope with the complexity of the world. I call this the *paradox of working memory*.

A traditional strategy to overcome this paradox is the aforementioned chunking. Chunking is a way to enlarge a representational unit of attention so that more items of information can be processed with the same WM capacity. For example, although a random sequence of alpha-numerical letters are difficult to remember and process due to the limited capacity of biological WM, once they are chunked into a meaningful sequence, they can be remembered easily. Thus, a seemingly meaningless sequence of "CIAUCLAKGB" can be remembered easily by means of chunking; they are chunked into "CIA," "UCLA," and "KGB". Chunking thus enlarges the conceptual unit of attention by means of LTM. Although linguistic chunking is well known, it is not the only chunking. Information can be *visually* chunked if visual information is stable over time (Magnuson et al., 1998). Such expanded STM capacity with the assistance of non-STM, such as LTM, is called *compound STM capacity* (Cowan, 2001). Visuo-spatial information can be chunked both verbally and visually. Chunking itself *is* a partial solution to the paradox of working memory.

The question is "is chunking sufficient to overcome the limitation of WM?" It does not seem so, first because the world contains a lot of visual complexity that cannot be verbally chunked and second because the world is not stable enough to enable visual chunks to be formed. This can be seen in change blindness (Simons et al., 2005). Change blindness refers to the surprising difficulty observers have in detecting a significant change to their visual field. In the experimental setting, usually two different pictures flicker quickly. Although there is a significant difference between them, a large portion of subjects, to their surprise, does not detect the change. In the change blindness cases, the reason why participants cannot detect the change is precisely due to the instability of the scene. And they do not seem to linguistically chunk the visual stimuli. If they could chunk visual information perfectly in order to account for every visual stimulus into four items of information, they would detect every single change. Although whether this is a case of "blindness" characterized by lack of experience is a controversial issue (Block, 2007, 2011), it is relatively clear that there is no cognitive access to the change (because we are not "aware" of the change). Thus, it seems that chunking alone does not solve the paradox of working memory. We are then brought back to the paradox.

External Working Memory and Spractions

How can we solve the paradox, then? I argue that the solution to the alleged paradox is to view the external world – space, gesture, body, action, and so on – as constitutive part of material supervenience base of WM. Once we view the human agent and its immediate surrounding environment as a coupled cognitive system (Clark and Chalmers, 1998), the external features of the world *in the coupled system* can be regarded as constituting part of material supervenience base of WM (Rowlands, 1999). The external features of the world can temporarily maintain, allow for access, and update information necessary for ongoing cognitive activities. As a consequence, the external features of the world can functionally augment the limited capacity of biological WM. Because of the external features of the world, I argue, we can cope with complex real world situations, even if our biological WM capacity is severely limited. To cognize efficiently, in other words, we are naturally exploiting the external features of the world as a material supervenience base of WM function. There is no problem with chunking per se; I am proposing that it is only a partial solution to the problem. Once theoretically conjoined with the external WM, they together solve the paradox of working memory.

Biological WM has been believed to be augmented by LTM, the external features of the world, and such; this functional whole has been called *compound WM* (Cowan, 2001). Under the concept of compound WM, however, components other than biological WM, such as LTM and the external features of the world, are considered mere *causal part* of WM. That is, while the external features of the world, in which we are embedded, are important aids to WM, according to this view, they are not themselves constituents of WM (c.f. Rupert, 2004). I argue that components other than biological WM, especially the external features of the world, are indeed *constitutive part* of WM. The coupled system of biological WM and the external features of the world together constitutes functional WM; WM is actually extended into the external world (c.f. Hutchins, 1995).

Although it might seem trivial, the difference between 'causal' and 'constitutive' is important. Roughly stated, constitutive part of something is part of what it is to be that something, while causal part of something is not. Block (2007) illustrates this point as follows; "cerebral blood flow is *causally necessary* for consciousness, but activation of the upper brainstem is much more plausibly a *constitutive condition*, part of what it is to be conscious" (p.482; emphasis mine). The distinction of causal/constitutive in cognitive science is captured by the debate between extended cognition and embedded cognition (Rupert, 2004; also discussed in Clark, 2008). The hypothesis of extended cognition (dubbed as HEC in the literature) asserts that the external features of the world constitute part of material supervenience base of cognition; the hypothesis of embedded cognition (dubbed as HEMC in the literature) holds that the external features of the world are causally relevant to cognition but do not themselves constitute part of cognition.

	External WM	Compound WM
External World is …	Constitutive part of WM	Causal part of WM
Hypothesis of …	Extended cognition (HEC)	Embedded cognition (HEMC)

Table 1. The conceptual difference between external WM and compound WM.

The original idea of external WM comes from Rowlands (1999). Using George Miller, Rowlands argues that biological WM is enormously limited, unstable, and unreliable so the main locus of WM should actually be external information-bearing structures. Challenging Rowlands, Rupert (2004) claims that external WM is not plausible, while compound WM is, based on the fact that the nature of the contributions of the biological WM and external features of the world are profoundly different. As Clark (2008; also Clark and Chalmers, 1998) argues, however, externalism does not demand fine-grained functional similarities of the inner and outer contributions. While precisely how WM is offloaded is debated (Gray et al., 2004; Gray et al., 2006), the general upshot, then, is that WM is externally distributed if the external features of the world constitute part of material supervenience base of WM, even if functional similarities are not fine-grained.

According to computational cognitive science, the basic function of cognition is largely accounted for by two main factors; computation and representation (c.f. Horst, 2011). The concept of computation and representation naturally applies to WM as well. By means of representation and computation, WM can store, update, and access information necessary for ongoing cognitive activities. Then, there are two ways how we externalize WM; by externalizing computation and by externalizing representation. Having said so, it is important to note that computational function and representational function do overlap (McClelland et al., 1986; Clark, 1989, 1993) so that the distinction is merely ideal-typical.

We seem to be naturally offloading complex computation onto the external world if it is an available option (Gray et al., 2004; Gray et al., 2006; Wilson, 1994). For example, although we can rotate objects mentally (Shepard et al., 1971), it is more efficient (faster and more accurate) to do so physically. The ubiquity of physical rotation as computational action is found by Kirsh and Maglio (1994). It seems that we use external computation when WM load is heavy (Kirsh et al., 1994). Also, we offload WM representational function by exploiting the stability of the world. That is, by leaving information in the external world, we reduce the WM load the biological WM has to process, as the external world is too complex to process in the biological WM. In a way, we use the world as its best model, as roboticist Rodney Brooks once put (1991). In a block-copying-task (Ballard et al., 1992), subjects are asked to replicate a model shown in the model box in the workspace, using blocks in the resource box. Eye-movement tracking reveals that subjects look at each box many times, the same pattern found in the eye-movement tracking of the change blindness experiment. A natural interpretation is that we do not construct detailed internal representations of the external world, because the world is reliably there and representing the external world accurately exceeds the WM capacity.

From the 'load theory of attention', it is known that appropriately directing attention requires the active maintenance of stimulus priority in WM (De Fockert et al., 2001). Under high WM load conditions, then, it is difficult to maintain stimulus priority. As a result, more distracters are processed in WM. In other words, as WM load increases, we get more confused. This is a dilemma, since at the perceptual level (i.e. early selection), heavier (visual) load, or more visual information processing, reduces distracters (Lavie, 1995). When the world is visually complex, however, there is likely a heavy WM load and overflow of information at the cognitive level (i.e. late selection). Tversky (2010) argues that gestures, use of tools, and reconfiguration of the space will help us cognize, because they abstract, schematize representations, and facilitate our attention. That is, by means of abstracting and schematizing, attention is directed only to important aspects of the world. Tversky calls such abstracting/schematizing actions *spractions* (space-abstraction-action). Actions onto the external world, such as gestures, use of tools, and manipulations of the world, facilitate directing WM level attention only to relevant aspects of the world to the task at hand. That is, via spractions, WM load is offloaded onto the world (c.f. epistemic actions of Kirsh and Maglio; 1995). The hypothesis entailed is that, as WM load increases (as the world gets visually complex), people offload it onto the world rather than process it internally, although it is in principle possible to process it internally. Consequently more spractions (or epistemic actions) are likely to be observed.

Experiment

To test whether/how we are offloading WM onto the world, subjects were asked to build Lego blocks and the way they used the space – use of spractions – was analyzed. Lego was chosen because Lego block assembly consists of pattern matching, planning, decision-making, and problem solving, all of which rely on WM. As the model used in the experiment targets young children, WM load is assumed relatively light. If offload of WM load is observed in this experiment, it can be generalized to many of daily situations, which have higher WM load.

Method

The basic methodology used here is generally called cognitive ethnography (c.f. Ball et al., 2000; Hollan et al., 2000; Kirsh, 1999; Kessell and Tverksy, 2010). It differs from the traditional ethnography in that it emphasizes specificity, purposiveness, and confirmation (Ball et al., 2000). Rather than observing a field without prior knowledge or theory, cognitive ethnography relies on small-scale data collection based on representative time slices of the domain of interests that is confirmable. Instead of thick description (Geertz, 1973), participants' activities were videotaped to be analyzed. To guarantee the objectivity of analysis (and consequently confirmation), codes were devised, and Cohen's Kappa ($0 \leq K \leq 1$) was calculated. Codes were devised so as to pick up spractions. Cohen's Kappa is an indicator of inter-coder agreement; as Kappa is higher, coders interpret the same data more similarly, and thus analysis is considered more objective. It turned out that Cohen's Kappa was 1.

Participants

Total 6 female students from the same graduate school participated in the experiment on a voluntary basis. All participants agreed on being videotaped. They were all in their twenties when the experiment was conducted. They were all naïve as to the purpose of the study. They all signed an informed consent approved by the University Institutional Review Board (IRB).

Material

Lego Technic 8065 (target age 7-14) was used for the experiment. It was selected for a pragmatic reason. It can be easily completed within one hour. Subjects were asked to build Lego Technic 8065 based on the instruction manual while being videotaped. Two different models can be built out of Lego Technic 8065. All were given the instructions for one of the models. Although some instructions instruct to sort blocks in advance, this one does not.

Results

Although it is possible to process information internally, it was observed that participants constantly engaged in one or more of spractions over the videotaped session. That is, they constantly used the external space as external WM. Out of six participants, five did sorting regardless that the instructions did not say to do so (some Lego instructions instruct to sort blocks in advance). Two did sorting in advance only; one did sorting on demand only; two did both. One did not do sorting at all; she made a significant number of mistakes. Although the sample size is too small to make a generalization, sorting seemed to help participants to think. As sorting is time-consuming, if viewed purely from the pragmatic perspective, it is disadvantageous (c.f. Kirsh and Maglio, 1994). Also, in principle it can be done in the head. Regardless, the participants did sorting. All the participants separated assembled blocks from the resource pool. This pattern was consistent. When there was more than one assembled block, they were grouped together and placed separated from not-yet-assembled blocks.

All of them looked at the instruction and/or model after picking up a piece. Although it was difficult to follow participants' eye movements, it was a consistent pattern that all the participants looked at the instruction and the model many times after picking up a desired piece. In most cases, they first looked at the instruction to pick a piece. Once they picked up a desired piece, they again looked at the instruction to see where it fit. Although it is possible to process both types of information simultaneously (i.e. which piece and where it goes), looking at the instruction once, it does not seem cost-effective given the stable world is out there and given that making detailed mental representation seems time consuming. It seems that use of external representation was commonplace. This finding is consistent with the theory of the limited WM capacity and previous experiments, such as block-copying task.

All of them did physical rotation and alignment following the instruction. When the model in the instruction was flipped, participants flipped their model as well. Although the instruction instructs to rotate, it does not instruct to align the model to the instruction. All the participants consistently aligned the instruction and the model under assembly. Such actions (alignment and rotation) are disadvantageous if they are taken purely as physical actions (c.f. Kirsh, 1995), but clearly have epistemic advantage. Although the Lego Technic 8065 is relatively simple (target age is 7-14), it still is too complex to mentally manipulate accurately. Physical rotation and alignment are clear cases of spraction.

One participant counted the number of holes by using another piece as a counting tool. She had to connect two parts by putting two bars into holes; there were thirteen holes, and bars had to be connected to the fourth and sixth holes respectively. She counted the number of holes on the instruction booklet with the piece. All the participants compared a piece with the booklet by placing the piece on the instruction, at least once during the assembly. Length is oftentimes overestimated or underestimated (Jones et al., 2006). It is thus difficult to accurately represent length mentally (WM load is heavy). The accurate length is printed on the instruction (obviously for measuring purpose). Consequently, all the participants compared the length of a piece with the instruction by placing it on the instruction.

Discussion

The world is full of complexity and we have to survive in such a complex world. The complexity of the world easily overwhelms the capacity of biological WM (Kessell and Tversky, 2010). Biological WM alone, then, does not seem to suffice for us to live a normal, smooth daily life. People exploit the external world as the material superveniece base of WM by means of spractions. People gesture, arrange the world, and make symbols and artifacts. Spractions and their consequences, such as reconfigured space, augment the limited biological WM capacity. WM then is not an equivalent concept to biological WM but it consists of biological WM and the external features of the world (and perhaps more, such as LTM). Both the brain and the world can serve as the material superveniece base of WM (c.f. Rowlands 1999). There is no qualitative difference between the external features of the world and the biological WM.

To observe how external WM plays out in reality, participants of the experiment were asked to assemble Lego blocks in front of a video camera. The analysis of the videotaped session revealed how they used the external world as external WM. They externally did what they in principle could do mentally. For example, they looked at the instruction after they picked up a desired piece to see where it is assembled. In principle, one gaze suffices to construct a mental representation of the external world. However, they referred back and forth between the piece and the instruction diagram. Similarly, they sorted blocks before assembly. In principle, sorting of pieces can be done purely mentally (if you have a photographic memory, you can in principle memorize all the patterns and locations of pieces on the table and classify them according to some manner). However, as the capacity of biological WM is limited to about four items of information, and Lego block assembly requires processing of more than four items of information, it seems participants externalized (offloaded) their cognition onto the world. Overall, spractions were observed constantly over the videotaped session. As the model used in the experiment target children between 7 and 14 years old, WM load is assumed relatively light. As many of daily situations are assumed to have higher WM load, it is inferred that offload of WM functions is ubiquitous in daily life.

The idea of externalization of WM function might be challenged on the ground that some people can do tremendous amount of information processing in the head alone without externalizing WM function. For example, some expert abacus users can multiple large numbers within a minute. Rumelhart et al. (McClelland et al., 1986, chap. 14) speculate that the ability to do information processing that seems too difficult to do in the head derives from the ability to do so externally; they are merely visually imagining what we do externally. Frank et al. (2011) confirmed this. That is, mental calculation by abacus users involves visual manipulation of imagined abacus.

Furthermore, they demonstrated that the amount of visual information abacus users process in the head cannot exceed the capacity limit of the biological visuo-spatial WM (in their case, 3). Thus, the fact that some people can do tremendous amount of information processing in the head without relying on the external world does not seem to constitute a counterexample.

We can calculate the amount of distributed WM-based cognition. The amount of externalized WM-based cognition is equal to the relevant amount of information for a given cognition minus four chunked items, the items of information the biological WM can process, or

$$y = z - \sum_{i=1}^{4} x_i,$$

where y is the amount of distributed cognition (measured in the number of items), z is the number of items (cognitive load) demanded for a task at hand, and x_i is chunked items of information processed in the biological WM.

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