The bouncer in the brain

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Efficiency variations in the filtering of relevant from irrelevant information could contribute to individual differences in working memory. A new functional imaging study suggests that the basal ganglia act as this filter because activity in this region before stimulus presentation was inversely correlated with unnecessary storage.

Anyone who has ever fumbled to remember an unfamiliar phone number without the benefit of pen and paper knows that our capacity for holding information 'online' in a highly accessible state is strictly limited. This capacity is called working memory, and several decades of work suggests that its capacity is limited to about three or four items[1,2]. Nevertheless, individual differences in memory capacity correlate robustly with measures of fluid intelligence and scholastic aptitude[3], which has motivated widespread interest in the source of these capacity limits.

One perspective on individual differences in memory capacity views variation in terms of the number of 'slots' that are available for short-term storage. However, apparent capacity differences might also be explained by variations in the efficiency with which information is selected to fill this limited workspace. A useful analogy for understanding the difference between these two ideas is the difference between the space that is available in an exclusive nightclub and the effectiveness of the bouncer who grants admission. From this perspective, high-capacity individuals may have a better bouncer rather than a larger nightclub. In this issue, brain imaging evidence from McNab and Klingberg[4] implicates a specific neural region that may serve as the bouncer for the mind.

This hypothesis is consistent with a growing body of evidence that shows tight links between attention and working memory. Some theorists have even suggested that they are essentially the same mechanism[3]. This viewpoint is supported by the strong overlap in the cortical areas that are active during attention and working-memory tasks, as well as evidence that directly implicates attention in the active maintenance of information in working memory[5]. Furthermore, an individual's working-memory capacity is highly predictive of his or her performance on a wide range of attention tasks[6]. Across the board, individuals with high working-memory capacity tend to excel at focusing attention on relevant information, whereas low-capacity individuals tend to be more easily distracted by irrelevant information. Indeed, these differences in attentional ability may actually be the reason for differences in memory capacity. That is, attention may control the flow of information into working memory so that only the most relevant information for the task at hand (such as finding car keys) consumes this limited storage space. Thus, a weak attentional bouncer may result in the working memory being continually overloaded with irrelevant information. The counterintuitive aspect of this idea is that low-capacity individuals may actually hold more information in working memory than high-capacity individuals, but it may simply be the wrong information for the current task.

This idea is supported by an experiment in a previous study[7], in which individuals tried to voluntarily control what information from a display would be stored in working memory. In one experiment, observers were asked to remember only the red items. On some trials, they were shown red items (either two or four red rectangles) and could thus open the gates to working memory for all items in the display. On other trials, they were shown a mix of two red items and two blue items, which required them to selectively admit only the red items and to ignore the blue items. To measure how efficient a given individual was at keeping the blue items out of working memory, the

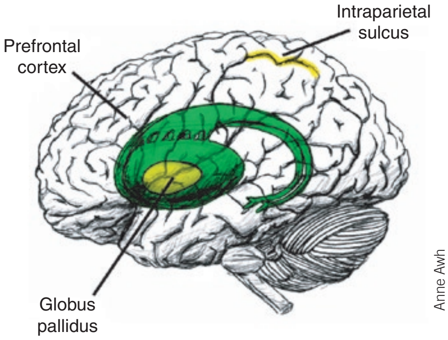

Figure 1 Sagittal view of the brain, depicting the position of the globus pallidus (yellow) in the basal ganglia (green), the intraparietal sulcus and the prefrontal cortex.

authors measured a scalp-recorded brainwave, which is a sensitive measure of the number of objects being currently remembered[8]. If an individual was perfectly efficient at excluding the irrelevant blue items, then the amplitude for the two red plus two blue trials should be identical to when only two red items were presented. On the other hand, if an individual was perfectly inefficient at excluding the blue items, then the amplitude for the two red plus two blue trials should be identical to when four red items were presented. The results showed that high-capacity individuals were extremely efficient at bouncing out the blue items from working memory and that the low-capacity individuals were unnecessarily storing the blue items in memory. These two factors showed a strong linear relationship, such that as memory capacity increased, the unnecessary storage of distractors decreased.

These results demonstrate a strong link between the efficient selection of information to be remembered and the capacity limit of individual observers. Moreover, these data are consistent with functional magnetic resonance imaging observations of activity in the

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intraparietal sulcus (IPS), a possible source of the memory-sensitive brainwave. Activity in the IPS reaches a peak when storage capacity in working memory has been exhausted[9,10], suggesting that this region is directly involved in the storage of information in working memory.

If the IPS can be conceived of as a capacity-limited nightclub, then where might the bouncer reside in the brain? McNab and Klingberg[4] addressed this question by using cues to inform subjects whether the ensuing display would contain irrelevant distractors. When the cues indicated that distractors would be presented, elevated activity was observed in the prefrontal cortex (PFC) and basal ganglia before the onset of the memory array. This filtering set activity was interpreted as a possible neural implementation of the bouncer. Indeed, activity in the PFC and basal ganglia showed a positive correlation with individual working-memory capacity, consistent with the notion that working-memory ability is intertwined with selection efficiency. The subjects who could hold more items in working memory were the same subjects who had higher levels of filtering set activity.

Finally, consistent with prior research, the authors identified a region in posterior parietal cortex that was sensitive to the number of items that were held in memory. This enabled the authors to measure the degree to which irrelevant items were stored in working memory by comparing this parietal activity in trials with and without distractors. The efficiency of the bouncer was quantified by comparing parietal activity in conditions where there were three target stimuli, with and without distractors. Increased parietal activity in the distractor condition provided an objective measure of unnecessary storage in working memory. Consistent with the previous study[7], individual working-memory capacity was inversely correlated with unnecessary storage in working memory. High-capacity subjects were less likely than low-capacity subjects to store the distractors in memory. In addition, a targeted analysis of the globus pallidus (a subregion of the basal ganglia) revealed that higher filtering set activity in this region was inversely correlated with unnecessary storage. Taken as a whole, these data highlight the possibility that the globus pallidus may be the bouncer of the mind.

The basal ganglia seem to be well-situated for such a role in excluding task-irrelevant information because they are closely interconnected with the PFC via a series of well-characterized loops[11]. Indeed, computational models propose that the basal ganglia provide a dynamic gating mechanism for working memory by transiently providing either an inhibitory or disinhibitory signal to the PFC[12]. This role for basal ganglia in working memory is thought to be much like its involvement in gating the selection of actions in motor regions of the PFC[13]. In addition, the involvement of the basal ganglia in selecting items to be remembered is consistent with evidence that this structure is important for a person's ability to shift between task sets (such as choosing between different plans of action in an otherwise ambiguous situation)[14], a process that is known to involve the active inhibition of irrelevant task sets[15]. Together, the PFC and basal ganglia may determine what information is on the 'guest list' for the current task, which then determines which items will gain admittance to the small working-memory nightclub in the parietal cortex. The McNab and Klingberg[4] study provides direct evidence for the basal ganglia and PFC in controlling the flow of task-relevant information into working memory. Moreover, their results help us to understand the neural mechanisms underlying individual differences in working-memory capacity. Individual variation in this capacity is well known to be associated with complex behavioral abilities such as cognitive control and fluid intelligence. Thus, this exciting new work suggests that these important cognitive differences between individuals may stem from variability in how well the basal ganglia and PFC interact to selectively bounce task-irrelevant information from working memory.

1. Luck, S.J. & Vogel, E.K. *Nature* **390**, 279–281 (1997).
2. Sperling, G. *Psychol. Monogr.* **74**, 1–29 (1960).
3. Cowan, N. *et al. Cognit. Psychol.* **51**, 42–100 (2005).
4. McNab, F. & Klingberg, T. *Nat. Neurosci.* **11**, 103–107 (2008).
5. Awh, E. & Jonides, J. *Trends Cogn. Sci.* **5**, 119–126 (2001).
6. Kane, M.J. & Engle, R.W. *J. Exp. Psychol. Gen.* **132**, 47–70 (2003).
7. Vogel, E.K., McCollough, A.W. & Machizawa, M.G. *Nature* **438**, 500–503 (2005).
8. Vogel, E.K. & Machizawa, M.G. *Nature* **428**, 748–751 (2004).
9. Todd, J.J. & Marois, R. *Nature* **428**, 751–754 (2004).
10. Xu, Y. & Chun, M. *Nature* **440**, 91–95 (2006).
11. Alexander, G.E., DeLong, M.R. & Strick, P.L. *Annu. Rev. Neurosci.* **9**, 357–381 (1986).
12. Hazy, T.E., Frank, M.J. & O'Reilly, R.C. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **362**, 1601–1613 (2007).
13. Mink, J.W. *Prog. Neurobiol.* **50**, 381–425 (1996).
14. Hayes, A.E., Davidson, M.C., Keele, S.W. & Rafal, R.D. *J. Cogn. Neurosci.* **10**, 178–198 (1998).
15. Mayr, U. & Keele, S.W. *J. Exp. Psychol. Gen.* **129**, 4–26 (2000).

Dynamin-independent synaptic vesicle retrieval?

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A new study proposes that synaptic vesicle endocytosis at a large synaptic terminal is partly independent of dynamin and GTP hydrolysis, suggesting a new mechanism leading to vesicle fission and maintenance of neurotransmission.

Among the most astonishing mutants in flies are the temperature-sensitive alleles of *shibire*. These mutants are paralyzed when their temperature is raised to 30 °C, yet they resume activity rapidly after their return to 25 °C. Their paralysis is mirrored by the trapped endocytic intermediates that decorate vesicle-depleted synapses of *shibire* mutants at the elevated temperature[1]. The dynamin GTPase encoded by the *shibire* gene has since been implicated as being important in endocytic events. Dynamin's GTPase activity is required to pinch vesicles off the plasma membrane once a critical curvature is reached during endocytosis[2]. Mutants and biochemicals that inhibit this 'pinchase' activity have become standard tools for assessing the importance of endocytosis at synapses and elsewhere.

In the current issue, Xu *et al.*[3] report an elegant set of experiments that led them to propose that at least some components of synaptic vesicle endocytosis operate independently of dynamin and GTP hydrolysis. The authors took advantage of the intracellular accessibility of the calyx of Held, a large nerve terminal in the auditory brainstem, to examine the dependence of synaptic vesicle endocytosis on dynamin. Notably, they found that several manipulations aimed to disrupt dynamin function blocked endocytosis only transiently. Synaptic vesicle endocytosis recovered, despite the continued presence of reagents that potently block dynamin function, and typically endocytic retrieval, in multiple systems.

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