What makes a prodigy?

Brian Butterworth

A PET study measures brain activity during calculation in a prodigy and non-experts. Unlike the controls, the prodigy showed activation in areas involved in episodic memory.

Until now, almost nothing was known about the neural basis of exceptional cognitive ability. In a pioneering study in this issue, Pesenti and colleagues have now used functional brain imaging to examine the calculating prodigy Rüdiger Gamm, and to compare his brain activity with that of normal control subjects as they perform mental arithmetical calculations[1]. Gamm is remarkable in that he is able (for example) to calculate 9th powers and 5th roots with great accuracy, and he can find the quotient of 2 primes to 60 decimal places. The authors found that Gamm's calculation processes recruited a system of brain areas implicated in episodic memory, including right medial frontal and parahippocampal gyri, whereas those of control subjects did not. They suggest that experts develop a way of exploiting the unlimited storage capacity of long-term memory to maintain task-relevant information, such as the sequence of steps and intermediate results needed for complex calculation, whereas the rest of us rely on the very limited span of working memory[2].

It is widely assumed that human working memory is a temporary mechanism for maintaining information related to the task at hand in visual and speech-based buffers. (The speech-based buffer needs rehearsal for maintenance.) Estimates based on immediate serial recall put the maximum average capacity of this buffer as 7 ± 2 unrelated items (for example, a string of digits or words)[3]. Furthermore, functional brain imaging has established that speech-based storage involves the perisylvian language areas[4].

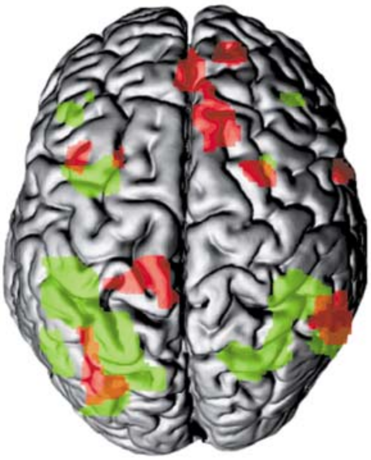
However, the kinds of calculation that Gamm is able to carry out accurately and quickly involve a sequence of steps and intermediate results well beyond the capacity of working memory. Like other calculating prodigies[5], Gamm has taught himself an enormous store of number facts. Most of us know our multiplication tables, and perhaps 50 simple additions[6], but Gamm has learned tables of squares, cubes and roots, among others. Similarly, Gamm has an enormous store of procedures and short-cuts that allow him to solve multi-step problems very quickly and accurately. For example, to solve 68 × 76 takes seven steps and six intermediate results. After some practice with the task, Gamm was taking about five seconds per problem—with a high degree of accuracy. Two-digit squares, by contrast, took him just over a second because they were simply retrieved from memory.

Such a sequence of operations and data handling would put a considerable strain on normal working memory, yet many types of experts show increased capacities for the temporary storage of task-relevant materials. For example, musicians can recall tunes after a single hearing, and expert waiters can keep in mind the precise orders for up to 20 people without writing them down (at least until the customer has paid). Experts develop a kind of 'long-term working memory' (LTWM), which is a domain-specific episodic memory. Thus, despite their other talents, the musician and the waiter score normally on tests of digit span, for example[2]. Similarly, whereas Gamm had a forward span of 11 digits (controls, 7) and 12 digits backward (controls, 6; ref. 7), his letter span was in the normal range. Language processing is perhaps a more familiar example of the ability to retain information beyond the span of short-term working memory. We can effortlessly retain meaningful sentences of 20 words or more, well beyond the span for unrelated words (about six) or words not in our language (about three). Several related accounts of this phenomenon propose cues in working memory for retrieving well-organised domain-specific information in long-term episodic memory[8].

Pesenti and colleagues now argue that Gamm has learned to use this LTWM facility to maintain task-related mathematical information. They used PET to study measure brain activity while Gamm (and six healthy non-expert controls of similar age) carried out complex calculations. The authors' hypothesis was that only Gamm would make use of long-term memory to store task-relevant information, and would thus activate brain structures implicated in the storage and retrieval of episodic memories. However, it was by no means obvious that a very high level of cognitive skill would necessarily invoke additional brain areas. Alternatively, the same areas that are active in normally skilled people could be more active in experts, or the same area could be somewhat extended (as is the case with musicians[9] or braille readers[10]). High skill could also mean that less brain activity is needed to carry out the same task[11].

It turned out that computation (compared to retrieval of memorized number facts) led to activation of an extensive bilateral visual processing system in both Gamm and the controls. According to the authors, this suggests that "during complex calculation, numbers are held and manipulated onto a visual type of short term representational medium." This contrasts with the more usual claim that "subvocal rehearsal is ... required for mental arithmetic"[12], but it may explain an earlier result showing that a brain-damaged patient could reliably add two three-digit numbers even though his digit span was reduced to two[13]. Several other areas were also specifically activated in both non-experts and Gamm during calculations, including areas identified in previous studies of non-expert subjects[14]. Complex

Fig. 1. Top-down view of the brain showing areas that are active in six non-expert calculators as well as Gamm (green), and areas that were specifically active in Gamm (red)[1].



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computations (for example, 32 × 24) additionally engaged a left parieto-superior frontal network, which may be involved in holding multi-digit numbers in visuospatial working memory, along with bilateral inferior temporal gyri, which is implicated in visual mental imagery. Furthermore, the left intraparietal sulcus and the precentral gyrus were activated, which may reflect the involvement of a finger movement representation network in the calculation process. This is not to say that these skilled adults are counting on their fingers, but it may be that the childhood use of fingers in learning to calculate somehow creates the neural substrate for later acquisition of numerical knowledge[15].

The most interesting finding, however, was that Gamm's brain showed task-dependent activation of four additional areas relative to control subjects. Three of these areas have previously been implicated in episodic memory processes: right medial frontal cortex, right parahippocampal gyri and right upper anterior cingulate gyrus **(Fig. 1)**. None of the control subjects showed increased activation relative to baseline in these areas. This supports the proposal that experts develop an ability to use long-term episodic memory to maintain task-relevant materials, rather as computers extend the capacity of RAM by using swap space on the hard drive to create a larger 'virtual memory'.

What does this tell us about the making of a prodigy? Frances Galton, in *Hereditary Genius*, proposed three factors, in necessary conjunction: "I do not mean capacity without zeal, nor zeal without capacity, nor even a combination of both of them, without an adequate power of doing a great deal of very laborious work." This probably corresponds to the popular view of genius. Of course, we all know it is ninety percent perspiration, but most of us also subscribe to what might be called 'the Mozart argument'; you cannot become a Mozart just by hard work.

Curiously, though, superior domain-specific innate capacity does not seem to have been relevant in Gamm's case, because he did not seem blessed with any particular gift for mathematics. As a result he lost interest in mathematics until about the age of twenty, when he came across an algorithm for calendrical calculation, working out the day of the week for any date, past or future. He practiced it for fun, and then entered for a TV competition where he could win bets by solving various calculations. In preparation for the program, he started to train up to four hours a day, learning number facts and calculation procedures; he now performs professionally. It would be interesting to compare his abilities and their neural substrate with those of a calculator or gifted mathematician who has shown prodigious abilities from an early age. Is the use of LTWM and episodic memory structures the principal factor differentiating prodigies from normal people, and if so, at what age or stage does this occur? Gamm said that at school he was "very bad at arithmetic" because the teachers never explained the concepts in ways he could understand[10]. Being able to grasp the meaning, structure and relationship of objects in the expert domain seems to be critical in setting up easily retrievable structures in long-term episodic memory, just as it is in our mastery of language. This study, though focused on a remarkable individual, illuminates the unremarkable as well as the extraordinary skills we all possess.

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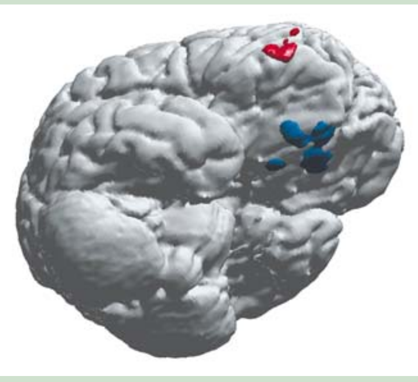
Reward and punishment in orbitofrontal cortex

Although skill at gambling is usually thought to concern people frequenting casinos in Las Vegas, it has real-world consequences as well. Patients with orbitofrontal cortex (OFC) lesions show pronounced deficits in 'gambling' tasks, in which they are required to make choices based on the previous likelihood of monetary gain or loss—and it is widely thought that such deficits underlie their inability to use knowledge of more abstract reward or punishment to guide real-life behavior; such patients are frequently disinhibited, socially inappropriate and irresponsible. Now, O'Doherty and colleagues (page 95) extend the idea that the OFC is critical in forming associations between stimuli and their rewarding or punishing outcomes. Normal human subjects participated in a gambling task while they were in an fMRI scanner. Using a sophisticated event-related design, the authors were able to measure an increase in the activity of the lateral OFC related to the subjects' receipt of punishment (after selecting a stimulus that caused them to lose money; red) and deactivation following reward. The authors recorded the converse pattern in the medial OFC (activation following reward, blue; deactivation following punishment). Therefore, reward and punishment may be processed in distinct subregions of the OFC. Furthermore, the magnitude of activation correlated with the magnitude of the reward or punishment. These results may help to explain why patients with OFC damage seem to be unable to represent the magnitudes of gain or loss, and thus have difficulty judging whether particular decisions are advantageous based on previous experience.



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