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Speed of Information Processing in a Calculating Prodigy

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Shakuntala Devi, one of the world's most prodigious mental calculators on record, past or present, is especially remarkable for the incredible speed with which she performs mental calculations on very large numbers. This rare phenomenon prompted the question of whether such exceptional performance depends on the speed of elementary information processes. Devi's rather unexceptional reaction times on a battery of elementary cognitive tasks, which were compared with the mean RTs of college students and older adults on the same tasks, contrasts so markedly with her amazing speed of performing huge arithmetic calculations as to indicate that her skill with numbers must depend largely on the automatic encoding and retrieval of a wealth of declarative and procedural information in long-term memory rather than on any unusual basic capacities. Some kind of motivational factor that sustains enormous and prolonged interest and practice in a particular skill probably plays a larger part in extremely exceptional performance than does psychometric *g* or the speed of elementary information processes.

It seems hard to believe, but the following is reported in the *Guinness Book of Records* (1982), which has a reputation for the authenticity of its claims: "Mrs. Shakuntala Devi of India demonstrated the multiplication of two 13-digit numbers of 7,686,369,774,870 × 2,465,099,745,779 picked at random by the Computer Department of Imperial College, London on 18 June 1980, in 28 s. Her correct answer was 18,947,668,177,995,426,462,773,730."

An article in the *New York Times* (November 10, 1976, cited in Smith, 1983, p. 306) reported that Shakuntala Devi added the following four numbers and multiplied the result by 9,878 to get the (correct) answer 5,559,369,456,432:

25,842,278
111,201,721
370,247,830
55,511,315

She was reported to have done this calculation in "20 seconds or less."

At Southern Methodist University, in 1977, Devi extracted the 23rd root of a 201-digit number in 50 s. Her answer—546,372,891—was confirmed by

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calculations done at the U.S. Bureau of Standards by the Univac 1101 computer, for which a special program had to be written to perform such a large calculation (Smith, 1983).

I first learned of Shakuntala Devi many years ago in *Time* magazine (personal communication, July 4, 1952). I was amazed, but also rather skeptical, that anyone could extract cube roots of large numbers entirely in one's head in a matter of seconds. Many years later I read biographical sketches of Devi in books on famous calculating prodigies, by Barlow (1952) and Smith (1983).

Then, in 1988, Devi visited the San Francisco Bay Area, when I had the opportunity to observe a demonstration she gave at Stanford University before an audience filled with mathematicians, engineers, and computer experts, who had come with their electronic calculators or printouts of large problems that had been submitted to the University's main-frame computer.

I was curious, first of all, to see if Devi had the kind of autistic personality so commonly associated with such unusual mental feats. Also, I wanted to measure her performance times myself, to see if they substantiated the astounding claims I had read of her calculating prowess. But mainly, if the claims proved authentic, I hoped I could persuade her to come to Berkeley to be tested in my chronometric laboratory, so we could measure her basic speed of information processing on a battery of elementary cognitive tasks (ECTs) for which the results could be compared with the reaction time (RT) data we had obtained on the same ECTs in large samples of students and older adults. Indeed, Devi kindly consented to come to my laboratory and spent about 3 h taking various tests. In addition, she spent some 2 h with me, discussing her life and work.

Speed of Performing Arithmetic Calculations

At her Stanford appearance, Shakuntala Devi, in a colorful silk sari, sat at a table in front of the blackboard in a lecture hall. The demonstration lasted almost 90 min. (Engaging in such intense mental activity beyond that length of time, Devi said, she begins to feel tired.) Problems involving large numbers were written on the blackboard by volunteers from the audience, many of whom knew of Devi's reputation and had brought along computer printouts with the problems and answers. Devi would turn around to look at a problem on the blackboard, and always in less than 1 min (but usually in just a few seconds) she would state the answer, or in the case of solutions involving quite large numbers she would write the answer on the blackboard.

Seated in the first row nearest to Devi, I was equipped with a HP computer and a notebook. Beside me, my wife held a stopwatch to measure Devi's solution times, while I copied problems from the blackboard. (Devi solved most of the problems faster than I was able to copy them in my notebook.) Solution times were measured as accurately as possible with an ordinary stopwatch. When occasionally it was not exactly clear just when Devi began to work on a problem, this was noted, and in those instances the time is not reported here. The solution times in those cases, however, were not atypical of the times that could be accurately measured. It should be noted that Devi's actual solution times might have been either under- or overestimated in many instances, because we had no control of the specific form of her responses, which varied from problem to problem. In every case, timing began as soon as the whole problem had been presented, and ended the moment Devi had given the complete answer. But she often preceded her answer with a phrase such as "The answer is . . .", or "That could be . . .", or "That was a (Friday)." Thus the problem may have been solved either entirely before these initial utterances or in parallel with the brief statement preceding the answer. Also, when large problem resulted in solutions that were quite large numbers, Devi would write out the answer on the blackboard, always quickly, and there was no way of telling whether the answer was complete in her mind before she began to write or the problem was being solved sequentially while she wrote out the answer. Since timing stopped only on the completion of the answer, the reported solution times, if anything, are probably slightly overestimated. Yet these were only a matter of seconds, and never as long as 1 min in the entire performance.

When I handed Devi two problems, each on a separate card, thinking she would solve first one, then the other, my wife was taken by surprise, as there was hardly time to start the stopwatch, so quick was Devi's response. Holding the two cards side-by-side, Devi looked at them briefly and said, "The answer to the first is 395 and to the second is 15. Right?" Right, of course! (Her answers were never wrong.) Handing the cards back to me, she requested that I read the problems aloud to the audience. They were: (a) the cube root of 61,629,875 (= 395), and (b) the 7th root of 170,859,375 (= 15). I was rather disappointed that these problems seemed obviously too easy for Devi, as I had hoped they would elicit some sign of mental strain on her part. After all, it had taken me much longer to work them with a calculator.

But cube roots could almost be called Devi's specialty. To "warm up" she requested a large number of cube root problems, that is, extracting the cube roots of large numbers, mostly in the millions, hundreds of millions, and trillions. The average time Devi took for extracting all of these cube roots was just 6 s, with a range of 2 to 10 s. Some examples:

$\sqrt[3]{95{,}443{,}993}$	Ans. 457	Time: 2 s
$\sqrt[3]{204{,}336{,}469}$	Ans. 589	Time: 5 s
$\sqrt[3]{2{,}373{,}927{,}704}$	Ans. 1,334	Time: 10 s

Then Devi took on more obviously difficult problems. For example:

$\sqrt[8]{20{,}047{,}612{,}231{,}936}$ Ans. 46 Time: 10 s

$\sqrt[7]{455{,}762{,}531{,}836{,}562{,}695{,}930{,}666{,}032{,}734{,}375}$

Ans. 46,295 Time: 40 s

In all of the above examples the numbers have here been marked off with commas, as is customary, for ease of reading. But Devi refused to accept large numbers marked off with commas, claiming that the commas break up a number artificially. For Devi, grouping the numbers in triplets by commas hinders the solution process. Hence the large numbers written on the blackboard for Devi were always strings of equally spaced digits, ungrouped in any fashion. A given large number, as she takes it in, rather automatically "falls apart" in its own way, and the correct answer simply "falls out." Apparently she does not apply a standard algorithm uniformly to every problem of a certain type, such as square roots, or cube roots, or powers. Each number uniquely dictates its own solution, so to speak. Hence the presence of commas only interferes with the "natural" (and virtually automatic) dissolution of the number in Devi's mind. I have since learned from an Indian professor that commas are not used in India's number system, and it seems likely that their interfering effect for Devi could stem in part from her intensive childhood experience in working with large numbers lacking commas or any other form of triplet grouping. Indians, my professor friend tells me, learn to group numbers mentally in terms of logarithms to the base 10, that is, 10^0, 10^1, 10^2, and so forth.

It will be noticed that all of the roots in the above problems are whole integers. But Devi also does noninteger roots almost as fast as integer roots—averaging about 3 to 4 s longer—provided the root is not an irrational number. For example, she could state the cube root of 12,812.904 as 23.4 almost without hesitation. Irrational roots, however are apparently more of a problem. She has reportedly done them, rounding off to two decimal places. But when the following number was presented at her Stanford demonstration, she took one look at it and dismissed it as a "wrong number." It was $\sqrt[9]{743{,}895{,}212}$. The answer (figured by computer) is an irrational number: 9.676616492+. I suspect that Devi could have solved it to at least two decimals, but the time required would have been too far out of line with her brief time on all the other problems to have made a good show. I got the impression that Devi's professional showmanship doesn't allow her to fumble over a problem or to spend much time on it if she sees that she can't solve it rather quickly. It is nevertheless interesting that she so quickly recognized that the 9th root of this nine-digit figure is an irrational number.

Devi also possesses the calendar skill that is frequently demonstrated by other calculating prodigies and by some so-called "idiot savants" or "autistic savants" (e.g., Hermelin & O'Connor, 1986). But I have not found any accounts in the literature of persons who can perform this feat so fast over such a wide range of dates, past and future. Given any specific date, Devi immediately states the day of the week it falls on. If the date was stated in the usual way (i.e., month, day, year) her average response time was about 1 s. But when the dates were stated to her in the order *year, month, day,* an ordinary stopwatch proved useless for measuring Devi's response times, because her answers came about as fast as one could start the stopwatch. To determine if anything besides sheer calculation enters Devi's thought process while she is doing calendrical calculations, I called out "*January 30, 1948,*" to which she instantly answered, "That was a Friday—and the day that our great leader Mahatma Gandhi was assassinated." Obviously her calendrical calculating does not entirely usurp her other memory or thought processes. Devi can also name, about as fast as anyone could articulate, all the dates on which a given day, say Thursday, falls throughout a given year; or name all the days falling on a given date each month throughout the year; and she did this in both the forward and the reverse temporal directions with about equal speed. The total times for these tasks ranged between 15 and 30 s.

Personal Characteristics. The first thing most observers would notice about Devi is that her general appearance and demeanor are quite the opposite of the typical image of the withdrawn, obsessive, autistic savant, so well portrayed by Dustin Hoffman in the recent motion picture, *Rain Man*. Devi comes across as alert, extraverted, affable, and articulate. Her English is excellent, and she also speaks several other languages. She has the stage presence of a seasoned performer, and maintains close rapport with her audience. At an informal reception after her Stanford performance, I noticed that among strangers she was entirely at ease, outgoing, socially adept, self-assured, and an engaging conversationalist. To all appearances, the prodigious numerical talent resides in a perfectly normal and charming lady. She is divorced and has a daughter attending college in England, who, Devi remarks with mock dismay, uses a computer in her science and math courses. In fact, Devi claims none of her relatives has ever shown any mathematical talent.

Shakuntala Devi was born in Bangalore, India, in 1940, to a 15-year-old mother and 61-year-old father, who was a circus acrobat and magician. Devi traveled with him since she was 3, performing card tricks, from which she cultivated her facility with numbers. Her talent in this sphere was manifested early; at age 5 she could already extract cube roots quickly in her head, and she soon began supporting herself and the rest of her family as a stage performer, traveling throughout India billed as a calculating prodigy. Even before she was in her teens, she began traveling around the world, performing numerical feats, usually before audiences in colleges and universities. She has written five books, three published in the U.S. (Devi, 1977, 1978a, 1978b). More biographical information can be found elsewhere (Barlow, 1952; Smith, 1983).

METHOD

Psychometric and Chronometric Tests

The various tests were administered by my research assistants (John Kranzler and Patty Whang), who had previously given all of the same tests to a great many subjects.

Psychometric. The Raven Advanced Progressive Matrices was administered without time limit, and the Digit Span subtests (forward and backward digit span) of the Wechsler Adult Intelligence Scale (WAIS) were administered in accord with the standard procedure described in the WAIS Manual.

Chronometric. As the main aim of the investigation was to assess Devi's speed of information processing on elementary cognitive tasks (ECTs), five different ECTs were used, varying in complexity and type of information processing demands.

Simple Reaction Time (RT1) was measured with an automatic computerized apparatus in which the subject's response console consisted of a semicircular array (15 cm radius) of eight green under-lighted pushbuttons and, at the center of the array, a "home" button. A flat-black overlay on the console covered all but one of the pushbuttons, exposing only the fifth button from the left as well as the home button. The trials were subject paced. A trial begins when the subject holds down the home button with the index finger of the preferred hand. After 1 s there is a preparatory stimulus ("beep") of ½ s duration followed by a random interval of 1 to 4 s, after which the reaction stimulus occurs, that is, the underlighted button going "on." The subject is instructed to turn off the light as quickly as possible by touching the button. RT is the interval between onset of the reaction stimulus and the subject's lifting her finger from the home button. Movement time (MT) is the interval between releasing the home button and touching the underlighted pushbutton located 15 cm above it. Following the tester's instructions, eight practice trials were given, then 20 test trials. RTs and MTs were automatically recorded in milliseconds by the computer, which calculated and printed out the median RT and median MT (RT1 and MT1) over the 20 test trials and also the standard deviation (SD) of RT and of MT (SDRT1 and SDMT1) as measures of trial-to-trial intraindividual variability in RT and MT. The computer also registered the number of erroneous responses.

Choice Reaction Time (RT8) was measured with the same apparatus, but with all eight pushbuttons exposed. Otherwise the procedure was the same as for RT1. The one button out of the eight alternatives that would light on each trial was selected at random, but every button was used with equal frequency. After eight practice trials there were 30 test trials.

The Odd-Man-Out (Oddman, for short), introduced by Frearson and Eysenck (1986), used the same apparatus and general procedure. But in this task, a set of *three* of the eight pushbuttons light up simultaneously, forming an oddity discrimination, always with two of the lights closer together than the third light, the "odd-man-out." The location of the odd light/button was randomized across trials. The subject's task was to touch the odd light as quickly as possible without making errors. There were eight practice trials and 36 test trials, and the same measures were recorded as in previous tasks.

The Visual Search (VS) and Memory Search (MS) Tasks were administered with a computerized binary response console. The stimuli (digits) were displayed on an IBM monochrome monitor, at eye level, about 2 ft in front of the sitting subject. The response console was a 20-cm square metal box with its top side pitched at a 15° angle for easy access to three round pushbuttons of 1-inch diameter placed in the form of an equilateral triangle, with 10 cm between the centers of the three pushbuttons. The button nearest the subject is the "home" button. Closely above each of the two top buttons are large-print labels: YES on the left and NO on the right. The task was subject paced, each trial initiated by the subject's pressing the home button. The console was interfaced with an IBM-PC and the entire sequence of trials was preprogrammed; median RT, median MT, the standard deviations (over trials) of RT and MT, and the percentage of erroneous responses were automatically computed and recorded.

In the VS task, the sequence of events was as follows:

1. To initiate a trial, subject presses down the home button and keeps it down.
2. 1-s delay.
3. A single target digit appears on monitor for 2 s.
4. Monitor goes blank for a random interval of 1 to 4 s.
5. A series of digits of a given set size (from 1 to 7) simultaneously appears horizontally on the monitor. Set size is randomized across trials. Following 16 practice trials, there were 12 test trials for each of the 7 set sizes, making 84 test trials in all.
6. The series remains on the screen until subject presses either the *YES* or the *NO* pushbutton. On half of the trials the correct answer is positive (*YES*) and on half of the trials the correct answer is negative (*NO*).
7. Instantly following the subject's *YES* or *NO* response, the word "Correct" or "Incorrect" appears on the screen for 2 s.

The MS task is exactly the same as the VS task except that the order of presentation of the single target digit and the digit series is reversed. All performance parameters on MS are obtained in exactly the same way as on VS.

RESULTS

Psychometric Tests

Raven Matrices. The Advanced Progressive Matrices (APM) is a highly *g*-loaded nonverbal test of abstract reasoning based on 36 multiple-choice items consisting of complex nonrepresentational figures. Its low to moderate correlation with complex measures of RT has been established in numerous studies (Jensen, 1982, 1987a; Vernon, 1987). It was administered to Devi with instructions to attempt every item and without time limit. She completed the test in 58 min, which is fairly typical for most subjects taking the APM under nonspeeded conditions. Her performance was unexceptional, being well within the range of the hundreds of university students tested in previous studies and on a par with older, college-educated adults.[1] Hence on this measure of psychometric *g*, Devi is not exceptional, in marked contrast to her phenomenal calculating ability.

Digit Span. The Digit Span subtest of the WAIS was of particular interest because it involves the recall of a series of digits immediately following their auditory presentation at the rate of 1 digit per second. Devi correctly recalled 9 digits forward and 4 digits backward. (The test is discontinued after failure on both trials at a given series length.) This performance also was not particularly exceptional, the combined score being at the 63rd percentile of the WAIS standardization sample in Devi's age bracket. The Digit Span score, however, is questionable because of a ceiling effect on the Digits Forward. Devi "topped out" on Digits Forward, in which the longest series is only 9 digits, and Devi correctly recalled 9 digits. The WAIS norms unfortunately do not give percentile equivalents for Forward and Backward Digits separately, but Devi's recall of 4 digits backwards is reported to be in the normal range for adults (Matarazzo, 1972, pp. 204–206).

Chronometric Tests

The results of Devi's performance on the various ECTs are shown in Table 1. As a basis for comparison are also shown the results on the same tests taken by college students, ages 18 through 25, and by 76 older adults from 51 to 87 years (M = 67.84, SD = 8.65), the latter group from a study done in Jensen's laboratory by Anada (1985). This group consisted mostly of university graduates and had a mean of 15.3 (SD = 3.2) years of formal education. While there are no sizable subject samples on these ECTs for persons in precisely Devi's age bracket, the present data are adequate for determining whether or not Devi's response latencies on these various ECTs fall within normal limits. Her feats of calculation, with their extraordinary speed of processing numerical information, are of course so far beyond the normal distribution of capability in mental arithmetic that she is considered in a class with only a handful of the world's greatest mental calculations, past or present, on whose performance we have authentic records (Smith, 1983).

Simple reaction time (RT1) essentially measures speed of stimulus apprehension as well as sensory lag, afferent and efferent neural conduction velocity, and

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[1]The precise score is not given, as I had assured Mrs. Devi beforehand that I would not report the exact scores she made on any of the published standardized tests used in this study.

TABLE 1

Shakuntala Devi Compared with Samples of College Students and Older Adults on Reaction Time (RT) and Movement Time (MT), in Milliseconds, on Various Elementary Cognitive Tasks

	Shakuntala Devi		a) Students (N = 213)				b) Older Adults (N = 76)				Difference[a]			
											Devi – a		Devi – b	
Chronometric Test	**Md. RT**	**Md. MT**	**Mean RT**	***SD***	**Mean MT**	***SD***	**Mean RT**	***SD***	**Mean MT**	***SD***	**RT**	**MT**	**RT**	**MT**
Simple (RT1)	272	277	270.60	29.23	140.78	69.98	337.53	48.64	321.38	88.6	0.05	1.95	−1.35	−0.50
Choice (RT8)	402	275	321.75	33.85	156.18	39.33	452.32	67.22	318.04	88.57	2.37	3.02	−0.75	−0.49
Oddman-Out RT	574	388	460.35	63.41	168.58	47.21					1.79	4.65		
	SDRT	**SDMT**	**Mean SDRT**	***SD***	**Mean SDMT**	***SD***	**Mean SDRT**	***SD***	**Mean SDMT**	***SD***				
Simple (SDRT1)	38	86	33.38	23.66	65.46	61.63	40.72	19.42	62.06	31.03	0.19	0.33	−0.14	0.77
Choice (SDRT8)	59	107	34.37	15.08	97.94	70.47	85.03	41.85	74.40	35.47	1.63	0.13	−0.62	0.92
Oddman-Out SDRT	201	185	78.45	35.48	139.93	60.58					3.45	0.74		
			a) Students (N = 48)											
Visual Search	**Md. RT**	**Md. MT**	**Mean RT**	***SD***	**Mean MT**	***SD***	**Mean RT**	***SD***	**Mean MT**	***SD***				
Positive	904	270	536.57	110.00	211.43	66.00					3.34	0.89		
Negative	972	258	593.29	145.86	213.29	78.71					2.60	0.57		
Both	939	266	564.93	129.18	212.36	72.76	743.22	157.91	363.34	138.53	2.89	0.74	1.24	−0.70
Memory Search														
Positive	**936**	**247**	**511.14**	**116.00**	**210.43**	**77.00**								
Negative	**1008**	**261**	**543.29**	**144.00**	**204.86**	**76.14**					**3.66**	**0.47**		
Both	**974**	**250**	**527.21**	**130.75**	**207.65**	**76.57**	**739.49**	**162.06**	**386.47**	**154.05**	**3.23**	**0.74**	**1.45**	**−0.89**
											3.42	**0.55**		

[a]Differences in standard deviation units.

muscle response execution time. On RT1 Devi's median RT is virtually the same as that of the students and is considerably faster (by 1.35 *SD* units) than that of the older adults. (The last four columns of Table 1 show the difference between Devi's RT (and MT) performance and the means of groups A (students) and B (older adults), expressed in units of each group's standard deviation.) On choice RT (RT8), which measures all the processes involved in RT1 in addition to the uncertainty of which light would go on and its discrimination from the other alternatives, Devi's RT (and MT) falls between that of the students and the older adults. The Oddman task involves all the processes in RT1 and RT8 plus the considerably more difficult spatial discrimination of the distances between the three lighted pushbuttons among the eight alternatives. Devi's Oddman RT and MT are both slower than the students'. (Comparisons with the older adults cannot be made, because the Oddman test did not exist at the time they were tested by Ananda, in 1985). The within-subject standard deviations of RT and MT (SDRT and SDMT) reflect trial-to-trial consistency of performance. SDRT has repeatedly been found to be moderately correlated with psychometric *g* (Jensen, 1987b).

Devi's error rates on both RT8 and Oddman were absolute zero. Students' mean error rates were RT8 = 0.52% (*SD* = 2.16%) and Oddman = 1.67% (*SD* = 2/68%).

The VS and MS tasks are of special interest, as they both involve numbers. VS measures the time taken to scan a series of from 1 to 7 digits to determine the presence or absence of a given target digit in the series. MS measures the time taken to scan a series of 1 to 7 digits held in short-term memory (STM) to determine the presence of absence of a single target digit. RT on these tasks is correlated −.30 to −.40 with the APM, and MT is correlated −.20 to −.30 with the APM, in the university student group with $N = 48$ (Jensen, 1987b). It may seem surprising that, although the VS and MS tasks both involve numbers, Devi's RT and MT on these tasks are notably longer than the mean RT and MT of the students, and Devi's RT (but not MT) is even longer than the mean RT in the group of older adults.

Of greater interest than the overall average RT on VS or MS, however, is the regression of RT on set size. It is now well established that RT increases as a linear function of set size for both VS and MS. The slope of the regression is considered a measure of the rate of visual scanning, or, in the case of MS, the rate of scanning information in STM (Sternberg, 1966). It is therefore of special interest to compare Devi with the other groups on the regression of RT (in ms) on set size (one to seven digits) for both VS and MS. The results are as follows:

	Visual Search		Memory Search	
	Intercept	*Slope*	*Intercept*	*Slope*
Devi	888	13	976	2
Students	467	25	429	24
Older Adults	567	50	569	45

Devi's MS shows hardly any slope, differing from the mean slope of the student group by 1.1 *SD*. Ordinarily, a very small slope in the MS paradigm would indicate a quite fast speed of memory search. But the very large intercept for Devi as well as her rather average RTs on all the other processing tasks suggests that her exceptionally low slope on MS is not due to unusually fast memory search but to some exceptional way of mentally representing the string of digits, made possible by Devi's vast knowledge of numbers.

The overall percentage error rates for Devi and the comparison groups were as follows:

Task	*Devi*	*Students*	*Older Adults*
VS	8.3	6.4	2
MS	2.4	6.3	4

Devi's very low error rate on MS also suggests that her encoding of the digit series in STM is probably better than the average in the two comparison groups. This is consistent with her superior performance on forward digit span, which also probably reflects her phenomenal knowledge of numbers.

DISCUSSION

From the conversation with Devi after the test session, I was impressed that she is a remarkable person, even aside from her phenomenal ability with numbers. Devi never attended school and has had no formal education, having been a stage performer since the age at which most children begin kindergarten. She has been self-supporting since childhood, has traveled all over the world on her own beginning in early adolescence, has written several books in English published by major firms, and is putting her daughter through college in England. And she has done it all by her wits and character. Moreover, it was apparent in our conversation that she has acquired a wealth of worldly knowledge and wisdom, and perhaps a certain shrewdness, that are far from ordinary.

But none of these observations nor any of the objective test results begins to explain why or how Devi is able to perform feats with numbers that are so far beyond what most of us can do in this sphere as to seem incredible. Her peculiar ability is indeed rare, perhaps one in hundreds of millions. Devi attributes her unusual career to "My love of numbers and my love of people." But then she immediately corrected this apparent slip of the tongue, "Oh, I should say it the other way around—my love of people and my love of numbers."

The question everyone asks is, how does she do it? Devi's own answers to this question, given at different times, seem rather inconsistent, but they may all be true. Variously, "a gift from God,"; or "an inborn gift,"; or "I think anyone could do it if they loved numbers the way I do,"; or "Perhaps anyone could do it if they had played with numbers for hours every day since early childhood." Devi's father discovered her fascination with numbers when she was 3 years old, and so he taught her arithmetic. Numbers and arithmetic were her favorite "toys" and she would do various calculations with them by the hour, every day, encouraged by her father, who soon made her a part of his professional act as a stage magician, with Devi performing card tricks and calculations. She soon became the whole show and her father then simply acted as her manager. All the while she was improving her calculating skills to be able to perform ever more amazing feats.

Although Devi is not, strictly speaking, a mnemonist, one may infer from the speed of her solutions that memory must play an important part in her skill. It is apparently not the "working memory" that is most exceptional, but the long-term memory (LTM), which must be extremely well stocked with highly overlearned and efficiently organized numerical information and various calculating algorithms. In short, for Devi the basic information processing limitations of normal working memory capacity have been largely overcome in the numerical domain by unusually efficient encoding and retrieval of numerical information in LTM. Devi's use of this vast accumulation of numerical information and algorithms for solving problems clearly evinces all the signs of being an extreme example of what Shiffrin and Schneider (1977) have described as "automatic processing," as contrasted with "controlled processing" of information.

While *controlled processing*, which characterizes the operations of working memory, is relatively slow and processes information sequentially, being able to process only quite limited amounts of information at one time and being unable to execute different operations simultaneously, *automatic processing* is fast, relatively effortless, and can handle large amounts of information and perform different operations on it simultaneously.

Most of the basic operations involved in Devi's performance probably became automatized during her childhood. She claims she could not teach anyone how she raises numbers to given powers or extracts various roots of given numbers, and the like, because she obtains the solution through exercising different routines drawn from an immense repertoire of numerical information and strategies, and the peculiarities of the problem itself determine the elements that are drawn upon from this repertoire to achieve the solution most efficiently. Any given number lends itself to the application of some "trick" through which the required solution is quickly arrived at. Perhaps hundreds of hours of specially devised experiments, using chronometric techniques, could possibly decipher some of the specific processes of Devi's skill that have become so automatic that she herself is unable to explain them in detail.

The memory load in Devi's large calculations must be enormous and obviously must be handled in a very different way than it would be by a novice at mental calculation. Devi "perceives" large numbers differently from the way most of us ordinarily do. When she takes in a large number (and she must do this visually), it undergoes some transformation, almost instantly—usually some kind of simplification of the number. But this is not a simple "chunking" of the number into smaller sets. In fact, Devi complained that dividing a long number up into smaller "chunks" only hinders her ability to do calculations on it. (Hence she hates the commas in large numbers.) This is not to say that Devi does not break up or analyze large numbers into some kind of numerical components, but only that she does not use any uniform type of "chunking" on every number. The unique properties of a given number mainly determine how it will "fall apart" so as to yield the required solution most efficiently. Devi demonstrates her idiosyncratic perceptions by spontaneously commenting on room numbers and automobile license plates. A four digit room number may be seen as the sum of, say, the cubes of two numbers, often in two or three different ways; or, if not the sum, a stringing together of the integer roots of two numbers, or a running product of the digits will pop into her mind. At times, when asked for the *n*th root of a given number, she would not only come up with the required answer, but while getting to the answer had also noticed other interesting features of the number (e.g., it is also the cube of one-half of the given number), which she would immediately volunteer. At a glance she "read" the number 720 on a car's license plate as 6 factorial (i.e., $6! = 6 \times 5 \times 4 \times 3 \times 2 \times 1 = 720$). And so it is for virtually every number Devi confronts. Each one evokes many associations and transformations, some more interesting to her than others. She especially likes the larger numbers, because they break up in more different and interesting ways, which makes them rather easier to work with. Extracting integer roots is easier than obtaining powers or doing multiplication, she notes, because extracting roots is a process of reduction—one always ends up with a smaller number.

Devi obviously does not go about her calculations in the same way that most of us would do. A simple experiment may afford those with rather average arithmetic skills a slight insight into how Devi operates so quickly with numbers. Most people have learned their times tables up as far as the numbers 12 or 13. This is easily shown by measuring response latencies; they are generally very short, but suddenly become much longer for multiplication tables beyond 12 or 13. The latencies for the 4s table (given in a random order) are rather uniformly short. But then we present $4 \times 23 = ?$ And here we see a relatively long response latency, because most people must perform the calculation 4×23 in their mind's eye, so to speak, in the same way as they would with a pencil and paper. But then we continue, and present 4×25. Here the response latency is again very short, like multiplying 4 by a single digit. Why? The subjects have never practiced memorizing all the multiplication tables through 25. But in their past experience they have acquired a number of automatic facilitating associations for this particular problem, 4×25, such as "25 is one-fourth of 100," or "four quarters is a dollar." These associations are automatically brought to bear faster than one is consciously aware, and the correct answer is immediately obvious—it simply pops into one's mind without intentionally performing a calculation.

Another example akin to calculation is the application of many complex grammatical rules in the construction of long or involved sentences. Most people speak their native language fluently and grammatically without being conscious of following grammatical rules, or even without any formal knowledge of grammar. Yet it would take a large computer with an extraordinarily complex program to perform this feat. For a calculating prodigy such as Devi, the manipulation of numbers is apparently like a native language, whereas for most of us arithmetic calculation is at best like the foreign language we learned in school.

The final puzzle is what produces a Shakuntala Devi? We know that with great amounts of practice high levels of expertise in various skills can be attained by quite ordinary people who are sufficiently motivated to engage in prolonged practice on a narrow type of skill. For example, Ericsson (1987, 1988) reports cases of quite average college students, with a memory span of 7 digits (forward), who, after some 200 practice sessions distributed over 2 years aimed at increasing their memory span, were finally able to recall digit series of over 80 digits after a single presentation. Most professional stage mnemonists, in fact, do not have that long a digit span.

Similar increases in skill with prolonged practice have also been demonstrated for mental calculating ability in studies by Staszewski (1988). College students with SAT-V and SAT-Q scores both near the 95th percentile were given systematic practice under laboratory observation on mental multiplication for about 45 min a day, 3 to 5 days per week, over periods of 2 to 3 years, totalling up to 300 h of practice. The students were guided to practice computational strategies that previous studies had revealed as the methods used by expert mental calculators (though not in Devi's league). The students practiced only multiplication, the hardest problems being the multiplication of five-digit numbers by two-digit numbers, with both oral and visual presentation. Average solution times on the hardest problems (2 × 5 digits) decreased from about 130 s at the beginning of practice to about 30 s at the end of practice. Even that is an unusual level of performance in mental calculation by normal standards, although it seems unimpressive compared to Devi's performance. But comparing Devi with persons who have had only 300 h of practice at calculating would be like comparing Vladimir Horowitz with persons who have practiced the piano only 300 h.

While extreme levels of expertise in any skill never seem to be found in the absence of enormous amounts of practice, what we do not know is whether the most extreme levels of expertise, such as Devi's, could ever be developed in almost any normal person picked at random and given the same amount of practice. It seems quite unlikely. If the amount of practice were the crucial variable, one must wonder why calculating prodigies of Devi's level are so exceedingly rare. Anyone who has had experience with preschool children knows how hard it is to get them to practice anything consistently, much less mental calculation. Yet Devi had practiced it enough by 5 to become a stage performer, astounding audiences by mentally multiplying large numbers, extracting their cube roots, and the like, with remarkable speed. It seems necessary to posit some initial, probably innate, advantage on which practice can merely capitalize. Rimland (1978), in theorizing about the psychology of autistic savants, has hypothesized that this advantage exists in the attentional system, as a trade-off in information processing between a narrow "band-width" of extremely high fidelity representation of the information input with undistracted processing of the information, on the one hand, and a wide band-width of relatively low fidelity but much greater breadth of awareness and generality of abstraction, on the other. By this notion, Devi as a child was able to operate in the high fidelity attentional mode when it came to mental calculation. She was not permanently locked into this narrow band-width, however, quite unlike the psychologically abnormal autistic savants, whose range and level of performance, incidentally, never approaches that of the psychologically sound persons, like Devi, who become great calculating prodigies.

But the nature of this hypothesized advantage is really still uncertain. It might well turn out to be characterized more as a motivational variable than as primarily an attentional or ability variable. Why did Devi as a girl practice numbers so assiduously? Or why did the young Richard Wagner, to the consternation of his parents and teachers, repeatedly play truant from school just to be able to spend whole days concentrating on the orchestral scores of Beethoven's symphonies? Or Ted Williams, the famous baseball player, whose mother worried about the normality of his running all the way home from school every day to practice until nightfall relentlessly pitching baseballs through a hole in a backboard? It is the same story repeatedly in the biographies of the world's truly exceptional performers in every field. A good case could probably be made that the most exceptional performers and creative geniuses are much further out from the average of the general population on some kind of motivational factor than on any traits most psychometricians would consider a basic ability or cognitive capacity.

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