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What Brain Imaging Reveals About the Nature of Multitasking

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Abstract and Keywords

The goal of this chapter is to provide an account of multitasking from the perspective of brain function and cognition using the new information gleaned from brain imaging science. By comparing the brain activation patterns observed in multitasking to the activation in the component tasks, it is possible to discover what is neurally distinctive and costly about multitasking. The neurocognitive account relates multitasking to the coordination of two large-scale cortical networks underlying each of the two tasks and a network of executive control. This approach provides new answers to several timeless questions about multitasking, such as the nature of the limited brain resources for which two tasks compete, the role of automaticity of one of the tasks being co-performed, and the brain effects of training.

Keywords: Multitasking, fMRI, brain imaging, brain networks, neural resources, neural mechanisms, training effects, executive function, automaticity

Because work and home environments often demand that several tasks be performed concurrently, the scientific study of multitasking has long been of interest. Multiple events in the natural and social environment often co-occur and need to be dealt with immediately and concurrently. For example, parents often have to attend to one or more children while simultaneously performing other domestic tasks. Another source of interest in multitasking research is that it explores the limits of human cognitive capacities. It is our good fortune that, to some extent, the human brain has the remarkable capability to follow multiple trains of thought at the same time. But this capability has severe limitations because human thought is not unbounded, and it is difficult enough at times to follow just one train of thought.

Multitasking opportunities have increased enormously due to the 21st century technologies that provide a myriad of information streams on various communication devices, multiplying the already multiple streams of available information that might potentially be attended to and processed. The availability of these multiple electronic information streams raises the question of what occurs in the human mind and brain when we try to process more than one stream of information at any given time.

In this chapter, we use the term *multitasking* (or *dual-tasking*) to refer to the concurrent *performance* of two or more cognitive tasks, and not just to passively experiencing multiple media stream inputs, such as interacting online while a movie is playing on TV. There must be two ongoing concurrent streams of active thought to qualify as multitasking according to our definition.

Although the number of available information streams has increased, the brain capability of concurrently processing multiple streams of information has probably not increased by much because the biological limits have not expanded. Multitasking usually results in at least one of the concurrent tasks being performed more poorly than when it is performed alone. Effective multitasking requires that two complex cognitive processes co-occur gracefully (p. 266) while sharing some common, resource-limited infrastructure. The scientific questions concern the nature of the co-occurring thought processes: how is competition between the two thought processes for shared resources resolved? Is the co-occurrence of the two processes facilitated by coordination mechanisms that are not an inherent part of either task? Can extensive training or experience improve multitasking performance? What are the determinants of individual differences in multitasking? Such questions have been asked for decades at the level of cognitive processes, but only recently has it become possible to address such issues at the level of brain function.

Explaining the neural bases of outstanding abilities such as multitasking is one of the illuminating contributions of the cognitive neurosciences. This approach has shed new light onto the extraordinary ability to process two concurrent streams of information at the same time. One inescapable aspect of multitasking is that it comes at a cost. Mental resources, like any other biological resources, are limited, and when they are distributed among the various functions that constitute multitasking, the ultimate cognitive performance in the component tasks is compromised.

Although biological resources are limited, cognitive resources can sometimes be extended through training, producing small-scale efficiency gains and large-scale strategy changes. It remains to be seen whether a new cohort of young multitaskers raised with multistream information technologies is more proficient at multitasking than their predecessors. It also remains to be seen whether the brains of highly experienced multitaskers are anatomically or functionally different from their less-experienced peers. In this chapter, we draw on recent noninvasive brain imaging research on multitasking to attempt to answer some of the questions just posed. In particular, we address these specific questions: (1) What limits the ability to multitask? (2) How does the automaticity of a task, described in terms of brain function, affect multitasking capability? (3) Can we train our brains to better perform multiple, concurrent tasks? (4) Are there individual differences that characterize the brains of successful multitaskers? The goal of this chapter is to describe what cognitive neuroscience can tell us about multitasking beyond specifying what brain areas activate during multitasking. Moreover, we will suggest a new conceptual brain-based framework to account for both behavioral and brain imaging findings.

A New Generation of Technologies and Multitaskers

The ubiquity of technologically based information streams, such as smartphones, tablets, multiple computer windows, GPS guidance systems, and digital music players, has made multiple information streams increasingly available for the human brain to process. But how such multiple streams can effectively be dealt with by our minds and brains has not been fully understood. Multitasking in technological environments was formerly a skill developed primarily by professionals working with electronic displays of electronically acquired data, such as radar operators using a cathode ray display of radar-sensed objects. Airplane pilots use radar and a variety of other types of displays to track the events in a system in order to plan their course of action while they maintain spatial, system, and task awareness (Wickens, 2002). Pilots have to develop the ability to multitask in order to be able to make life-or-death decisions in such environments.

The availability of a greatly increased number of multitasking opportunities raises the question of whether the Digital Age might be enhancing human multitasking abilities. There is currently a cohort that has grown up with the new technologies of cell phones, video games, music players, and so on, making them *digital natives,* in the sense that they are native speakers of the digital world (Prensky, 2001). Might their multitasking abilities be superior to those of previous generations by virtue of having more multitasking opportunities and experience early in their lives? Although there are no current scientific comparisons of the multitasking abilities of digital natives versus digital immigrants, there are studies that assess the effects of extended training on multitasking ability, which we will describe.

One particular type of new media multitasking is the playing of contemporary first-person action video games. Players must simultaneously process a myriad of visual information, command a video game character in first-person view through a fierce virtual battle environment, and converse with their adversaries. The games require rapid high-level processing of multiple streams of visuospatial information, culminating in rapid and accurate motor responses and enhanced visual processing abilities. Studies of people with a great deal of video game experience show that experienced gamers develop enhanced visual attention abilities (e.g., they are better at ignoring distracting stimuli; Green & Bavelier, 2007) and increased speed of visual (p. 267) processing (Dye, Green &

Bavelier, 2009; Green & Bavelier, 2003). Of course, people with extensive video game experience may well be self-selected for the relevant skills, and, in this way, they may be different to start with. But it is interesting that such visual processing abilities can be improved even in nongamers by extensively training them. With as little as 1 hour of video game playing per day for 10 consecutive days, participants with minimal previous video game experience showed expansion of their field-of-view and in the ability to detect visual stimuli presented in rapid succession (Green & Bavelier, 2003). We will later address the issue of gaming experience in relation to the issue of training and improving multitasking ability.

A Neurocognitive Perspective: A Conception of Brain Function Underpinning Cognitive Tasks

Using the new knowledge from functional magnetic resonance imaging (fMRI) studies about brain activity in multitasking, we will reframe explanations of the mechanisms and constraints underlying multitasking, many of which were previously developed with the benefit of only behavioral data. Under any perspective, multitasking requires more consumption of mental resources per unit time than does single tasking. By knowing what underlying biological resources are being consumed, we can develop a new type of account of multitasking within the framework of resource limitations in a neurocognitive system.

Brain imaging has changed the way we view human thought, and it has informed what we know about multitasking. Brain imaging has shown that human thought is unquestionably the product of many specialized brain centers working collaboratively; human thought is the epitome of a network function. For example, listening comprehension consists of the processing of raw auditory information in a brain center in primary auditory cortex, an auditory word-form processing center in posterior temporal and inferior parietal cortex, a word meaning and semantics center in posterior temporal cortex, a syntactic center in inferior frontal cortex, a visual imagery center in the intraparietal sulcus, a coherence monitoring center in medial frontal, and so on. Approximately 20–40 such centers activate in every cognitive task (although the precise count of centers depends on the granularity of the measurement). These centers appear as 20–40 clusters of fMRI-measured heightened activity in the brain. Whether it is the computation of an arithmetic result, the comprehension of a sentence, or the decision to take a financial action, many cortical centers are involved. Each center's contribution reflects its own specialization based on the inherent computational capabilities of that brain region and its previous experience in performing similar computations. A specialization can be thought of as high efficiency at performing some particular computation, such as the primary auditory cortex being specialized for computing information about temporal relations in acoustic signals.

The specialized computations of the individual centers are executed in interactive collaboration among the centers. The main evidence of the extensive collaboration between brain centers is that the activation among various subsets of the participating centers is synchronized; the activity levels of the synchronized centers rise and fall together, indicating that information is being transferred among them, thus coordinating their activity. Another indication of collaboration is that the effect of a factor (say, word frequency) that would be expected to affect the activation of one or two particular centers is typically observed in multiple centers (Keller, Carpenter, & Just, 2001); this suggests that the effects of factors are propagated among collaborating centers. It is this collaboration that makes human thought a network function.

The following principles are consistent with almost all fMRI studies, including studies of multitasking (see Just & Varma, 2007):

1. It is always a *network* of cortical areas, not just one area that activates in any task.
2. Each activating area is a computational center with a characteristic processing style (such as intraparietal sulcus processing of geometric information associated with spatial information).
3. The network of areas is self-assembled dynamically as a function of the task demands. For example, a language comprehension task includes a frontal-temporal network consisting of at least the left inferior frontal gyrus (L IFG) and posterior temporal gyrus, as well as the input sensory areas. This network automatically becomes activated whenever a person is exposed to utterances of their own language.
4. The activation in a task is synchronized between pairs or n-tuplets of participating areas. The communication pathways among areas are the brain's white matter, the tracts of myelinated axons enabling the close collaboration among activating gray matter areas. (p. 268)
5. Resource consumption (indexed by amount of brain activation) is modulated by cognitive workload. The more demanding the task, the greater the amount of activation in one or more areas.
6. The sensory and motor centers function in coordination with the "cognitive" centers in the sense that they concurrently activate with each other, and furthermore, the concurrent activation is often synchronized (rising and falling at the same time).

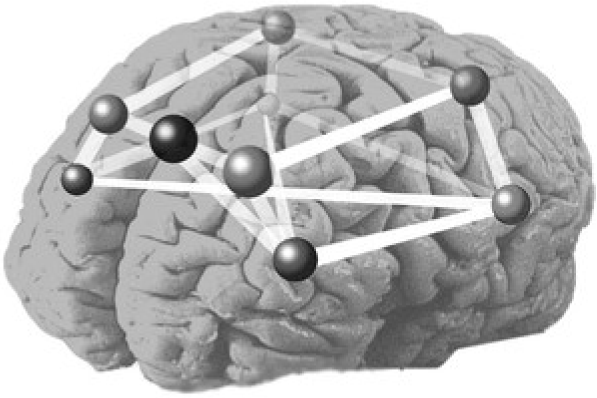

Fig. 14.1 Schematic depiction of a large-scale cortical network with the network nodes communicating via white matter tracts.

Figure 14.1 schematically depicts a cortical network of the human brain based on the neurocognitive perspective described. The colored spheres represent a set (network) of cortical areas associated with a hypothetical task; the white lines represent the channels (white matter) that enable communication between network nodes.

These principles of brain function also apply to multitasking, in which the network of activated areas involves two subsets of areas corresponding to the two component tasks. But what is particularly interesting is that the brain activity involved in performing two tasks at the same time is not a simple union of the activity underlying each of the two component tasks. Brain imaging studies make it possible to compare the activation underlying a dual task to the activation underlying each of the component tasks and to the union of the activation underlying each of the component tasks. Performing two tasks concurrently can be psychologically different from simply executing the processes associated with each task. Additional mechanisms and phenomena can come into play in multitasking. For example, multitasking could involve the addition of executive (frontal) functions that coordinate the execution of the component tasks, as one of the first fMRI studies of multitasking showed (D'Esposito et al., 1995). Or, the two component tasks could draw on common areas and thus compete for common resources. It is the combinations of the two task networks at the neural level that makes the brain basis of multitasking so interesting and determining of cognitive performance. As we consider various multitasking situations, we can ask how this neural chemistry shapes the resulting cognitive performance.

Our main contention is that the neural chemistry of performing two tasks concurrently is determined in large part by the availability or unavailability of appropriate brain resources relative to the specific resource needs of the component tasks that make up the dual task. Because the biological resources in a neurocognitive system are inherently limited, one cannot co-perform innumerable numbers of tasks concurrently without impacting performance. Thus, in our approach to understanding multitasking, we will try to specify which of the constituents of the neurocognitive system impose limits on multitasking. We will apply this approach in turn to the concurrent performance of various types of tasks, ranging from two simple reaction time tasks to listening to two people who are speaking at the same time.

Biologically Based Accounts of Multitasking

Brain imaging has afforded new ways of understanding the limitations on performing two tasks concurrently. Based on the neurocognitive perspective just discussed, one new perspective is associated with the brain's intercenter communication capacities that enable network functioning. Another new (p. 269) perspective concerns the limitations on the total brain work that can be performed per unit time. A third perspective concerns the change in timing of neural events during multitasking. These biologically based accounts of the limitation to perform simultaneous tasks are discussed in turn.

The discovery that cognition is a network function brought to light a previously covert resource that could constrain multitasking; namely, the communication resources that allow the various brain centers to communicate with each other. Interprocess communication occurs when brain centers communicate information to each other using the white matter tracts. The white matter constitutes about 45% of the brain by volume. It is composed of bundles of axons that have been myelinated, that is, coated with an insulating material that greatly increases the bandwidth of the axons (amount of information that can be transmitted without error per unit time). Even with myelination, there are bandwidth limitations on the communication between brain centers that reflect the capacity of the underlying white matter tracts.

Unlike behavioral studies, brain imaging studies can assess how much work the brain is performing (its cognitive workload) at a given time in a given situation at each of the participating brain centers. Thus, it is possible to compare the brain work in each of two single tasks to the brain work performed in the concurrent execution. Brain imaging studies suggest that there is an upper limit on how much brain work can be performed at any one time, and thus most tasks cannot be performed as well concurrently as they can alone. Brain imaging suggests an upper limit on the additivity of brain activation when two tasks are combined (e.g., Newman, Keller, & Just, 2007); in other words, the neural events occurring during the co-performance of two tasks are not just the co-activity of the two networks. Brain imaging also suggests that the timing of the underlying neural events can change during multitasking. There are also resource constraints on computation within centers. Each center possesses a finite supply of resources for storage and processing. The limitations on area resources and on the communication between brain areas underlie the performance degradation in multitasking, as described next.

Bandwidth Limitations

Bandwidth refers to the maximal rate of data transfer supported by a communication channel (Shannon, 1949). If the white matter communication channels are impaired in a neurological condition, then the bandwidth normally provided by those channels should be lowered. For example, a current theory of the neural underpinnings of autism proposes that the cortical communication bandwidth between frontal and posterior cortical areas is lowered in autism (Just, Cherkassky, Keller, & Minshew, 2004; Just, Keller, Malave, Kana, & Varma, 2012). In this view, people with autism should have a particular deficit during multitasking that involves frontal areas. One study compared adults with high-functioning autism to matched control participants on a multitask. But first, the two groups were equated on their performance in each of the two component tasks. The critical finding was that, in the dual task, the performance of the autism group was substantially poorer than that of the control group (García-Villamisar & Della Sala, 2002). The autism group, hypothesized to have a compromised cortical bandwidth, displayed a specific deficit in multitasking.

Given that any single task requires the use of interregional communication resources among participating brain areas, it follows that any dual task will increasingly draw on the capabilities of the white matter tracts. Thus, one possible new account of performance degradation in multitasking is that the communication among the brain areas involved in a multitask may be slower or more errorful. This would occur because the combined information flow from the two tasks may exceed the bandwidth of the communication channels.

To our knowledge, there are no brain imaging studies that have investigated the direct relation between the quality of the white matter tracts of a given person (e.g., some measure of the length or diameter of a specific tract connecting dual task–related areas) and their multitasking performance. One study of task-switching (which does not meet the definition of multitasking used here) found that the integrity of specific white matter tracts was a mediator of age-related changes in cognitive performance (Madden et al., 2009). Future investigations relating white matter tract properties and multitasking should clarify the limiting role of the brain's communication bandwidth in multitasking.

Limitations on Total Activation (Total Brain Work)

There is an obvious upper limit on how much thought can occur at any given time, a limit on one's total processing capacity. Some forms of high-level multitasking surely exceed this limit, as the decrements in dual-task cognitive performance (p. 270) (relative to single task performance) suggest. Brain imaging studies have suggested a simple account of higher level dual-tasking limitations: there may be an upper limit on the amount of activation in the brain that can be evoked at any given time. If performing one task alone activates some volume of the brain, say *x* voxels, and another task alone activates *y* voxels, then perfect additivity of the two tasks might be expected to activate $x + y$ voxels. But that is not what happens. Performing two simultaneous tasks typically activates substantially less than $x + y$ voxels. This effect has been called *underadditivity of multitasking activation* (Newman et al., 2007). The underadditivity is found even in dual tasks in which the brain networks for the two tasks (spatial processing and auditory language comprehension) are relatively non-overlapping (Just et al., 2001; Newman et al., 2007). The underadditivity of the activation and the performance decrements reflect the fundamental limitation on how much thinking can occur at any given time.

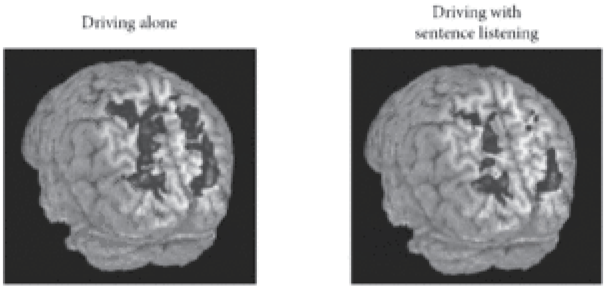

Fig. 14.2 The brain activity associated with driving decreases by 37% when the driver is also listening to someone speak.

The underadditivity of multitasking activation has been observed or implied in an interesting range of other combinations of high-level tasks: driving while listening to someone speak (Just, Keller, & Cynkar, 2008), performing mental rotation while listening to someone speak (Just et al., 2001; 2008; Newman et al., 2007), listening to two people speak at the same time (Buchweitz, Keller, Meyler, & Just, 2012), sentence comprehension and vowel identification (Mizuno, Tanaka, Tanabe, Sadato, & Watanabe, 2012), and performing dual *n*-back tasks (Jaeggi et al., 2007). In summary, there may be some upper limit on how much processing can occur at any given time when two concurrent tasks are being attempted. Assessing the total activation that an individual can sustain (in one or two tasks) may illuminate this issue.

Brain Imaging of Multitasking in Real-World Tasks

Cell Phone Use During Driving

One of the concerns about real-world multitasking involves the use of a cell phone during other activities, particularly driving. Cell phones have made conversations portable and executable anywhere within reach of a cell tower. But what is the impact of engaging in a cell phone conversation during driving? Because driving is an automatic task for an experienced driver, it sometimes feels as though there are ample cognitive resources left over to hold a conversation. But many behavioral studies (e.g., Strayer & Johnston, 2001) have shown unequivocally that driving performance is degraded by participation in a concurrent conversation. In a demanding driving situation, using a cell phone constitutes a very tangible risk.

What is it that occurs in a driver's brain if he or she is engaged in processing speech while driving? Driving while listening to a conversation partner was examined in one study by having participants use a driving simulator to steer a car along a winding road while having their brain scanned in an MRI scanner (Just et al., 2008). The main comparison was between a condition in which the participants were performing only the driving task versus driving while simultaneously listening to someone speak. The speech consisted of sentences (which were to be judged as true or false) referring to world knowledge.

The results showed that in the dual task there was much less activation associated with the driving task than when the driving task was performed alone. The decrease in brain activation from single- to dual-tasking was approximately 37% in the brain areas associated with the driving task. Figure 14.2 graphically depicts how listening to someone speak decreases the driving-related activation. This (p. 271) decremented activation due to multitasking was accompanied by a decrement in driving performance, measured as reliably poorer lane maintenance and more frequent hitting of the berm (Just et al., 2008).

Note that the implications of this study apply even to hands-free cell phone use. The dual-tasking limitations described here involved no physical manipulation of a cell phone; the language task involved only listening to someone speak. Having to additionally hold a cell phone, dial a number, or send a text message would almost certainly exacerbate that cost of multitasking during driving.

This finding raises the obvious point that if listening to sentences degrades driving performance, then probably a number of other common driver activities also cause such degradation, including activities such as tuning or listening to a radio, eating and drinking, monitoring children or pets, or even conversing with a passenger.

However, it is incorrect to conclude that using a cell phone while driving is no worse than engaging in one of these other activities. First, it is not known exactly how much each of these distractions affects driving, and it may indeed be important to compare the various effects and try to find ways to decrease their negative impacts. Second, talking on a cell phone has a special social demand because not attending to the cell conversation can be interpreted as rude, insulting behavior. There is an onus to keep the cell phone conversation going. By contrast, in a conversation with a passenger, the passenger conversation partner is more likely to be aware of the competing demands for a driver's attention and thus sympathetic to inattention to the conversation. Indeed, there is recent experimental evidence suggesting that passengers and drivers suppress conversation in response to driving demands (Crundall, Bains, Chapman, & Underwood, 2005). Third, the processing of spoken language has a special status by virtue of its automaticity, such that one cannot willfully stop one's processing of a spoken utterance (Newman et al., 2007), whereas one can willfully stop tuning a radio. These various considerations suggest that engaging in conversation while concurrently driving can be a risky choice, not just for common-sense reasons, but because of the compromised multitasking performance imposed by cognitive and neural constraints.

Listening to Two People Speak at the Same Time

One study examined the multitasking of two complex but highly automatic tasks: listening to two people speak at the same time (Buchweitz et al., 2012). Participants listened to a male voice speak a sentence in one ear and a female voice in the other ear. Although it is easy to "hear" both sentences, it is much more challenging to understand them both. The study compared the activation in the multitask to the single speaker case. The same set of areas was activated in the single task and multitask conditions. The study found not only an increased activation level in this set of areas for the multitask condition, but also an increase in the synchronization (relative to single tasks) between the key language-related cortical centers. Increased synchronization among activating brain regions with increased task complexity is a common finding, although complexity is often difficult to measure. However, in this case, the underlying cause of the increased complexity and the resulting increase in synchronization were identifiable.

In these listening comprehension tasks, in both the single and multitask versions, Broca's area (L IFG) and Wernicke's area (posterior left superior temporal gyrus [L STG]) both become activated. In the single task, the peak of the Broca's area activation typically occurs later (by about 1.6–2.0 s) than the peak of the Wernicke's area activation. The differences in their peak activations indicate that they are not completely synchronized, and that Broca's area lags behind Wernicke's area. However, in the dual task, the activation in Broca's area peaks earlier than in the single task, such that the peak activations of the two areas now differ by only 0.7 s. That is, they become more highly synchronized during multitasking. The interpretation of this finding of increased synchronization was that this shift in cortical timing may indicate more effective communication among the areas of the language network (Buchweitz et al., 2012). Figure 14.3 depicts the study paradigm and shows the changes in the timing of the peak activation for L IFG. More effective communication between the cortical centers involved in the task may have allowed the maintenance of a high level of performance in the dual task.

The mechanism of synchronization and effective communication may have been especially important for the participants in the study who had lower working memory capacity. The study identified a systematic difference among individuals in their amount of time-shift of their Broca's activation in the dual task. Those participants with lower working memory capacity for language displayed the larger shifts, perhaps because they were less able to keep the informational results of two areas co-active when there were twice as many results to be kept active. (p. 272)

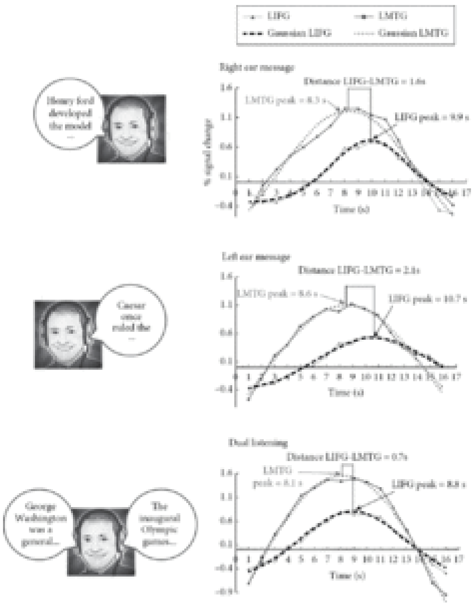

Fig. 14.3 Increased synchronization between Broca's and Wernicke's areas during multitasking.

What this study shows is that multitasking may be more than just a matter of doing more brain work. It may also be a matter of doing the work differently in adaptation to the doubled workload. Increased synchronization between areas activated in single- and dual-task performance was also reported in another study of language dual-tasking (Mizuno et al., 2012). Those authors suggest that the increase in synchronization between the specialized networks in the dual task (left dorsal IFG and superior parietal lobule) reflects greater and more complex demands being placed on the system.

It is important to note that many people are unable to perform two complex tasks concurrently while maintaining reasonable accuracy. This limitation applies to college undergraduates, who by virtue of their age and experience in computer use should be among the most effective multitaskers. For example, in the study of listening to two people speak at the same time, approximately 60% of the initial sample of students who were screened for possible participation in the study failed to accurately judge sentences as true or false at a level of at least 75% correct (Buchweitz et al., 2012). So, **(p. 273)** actually performing two high-level tasks at the same time is something that many people cannot do. Of course, almost anyone can listen to music while performing a nondemanding cognitive task. But as soon as the music listening requires active processing (such as detecting a particular sequence of notes), then performance declines to much lower levels. In many such task combinations, the accuracy is so low (often close to chance level) that there is no longer evidence that both tasks are actually being performed (i.e., that the input is being processed and a response is being generated). The fact that many people have difficulty with multitasking raises several interesting questions:

1. Are some types of tasks, such as automatic tasks, easier than others to perform concurrently?
2. Can extensive training improve multitasking performance?
3. Are there systematic differences among individuals in their ability to multitask, and if so, what basic cognitive abilities underpin individual differences in multitasking?

We address each of these issues in turn below.

Factors that Affect the Difficulty of Multitasking

Effects of Task Automaticity

Among the most important determinants of whether a high-level cognitive task can be performed concurrently with another task is its automaticity; that is, whether it can be performed without strategic control. Understanding speech in one's native language is an example of a complex task that can be executed automatically. Automaticity was first characterized on the basis of behavioral studies only. One of the key attributes of an automatic task was that it could be co-performed with another task, whereas a nonautomatic task could not be co-performed (Schneider & Shiffrin, 1977). When fMRI brain imaging became available, a more satisfying account of automaticity emerged. The contemporary view of automaticity contends that a skill or behavior becomes automatic when there is a transition from goal-directed behavior controlled by a frontal-parietal executive system to a state in which the frontal strategic control drops away. Here, we refer to tasks as being automatic if they do not require appreciable executive control by the frontal-parietal systems (Chein & Schneider, 2005). The strategic control mechanism entails processes executed in a small set of brain areas (bilateral dorsal prefrontal, left ventral prefrontal, medial frontal [anterior cingulate], left insula, bilateral parietal, and occipito-temporal [fusiform] areas). With this new perspective, we can now say that the *reason* that automatic tasks are more amenable to multitasking is that they have less need for network resources for strategic control, and thus they do not suffer from competition for this resource. The development of automaticity in a higher level task makes it more feasible that it can be performed concurrently with another task.

Automaticity occurs either as a result of deliberate training (Schneider & Shiffrin, 1977) or natural experience (e.g., listening comprehension). In either case, extensive practice is an essential ingredient, for two reasons. First, many component processes can become more efficient with practice, so that they consume fewer resources, manifested as decreasing levels of activation in many brain areas with extended practice. For example, in one study, the extra activation in the left inferior frontal junction in a dual-task compared to single-task condition decreased with practice; by the final training session, there was no significant difference in the activation between the dual- and single-task conditions (Dux et al., 2009). The second contribution of extensive practice to automaticity is that the component processes become self-scheduling or self-organized, no longer requiring the resources of the strategic control network. Because of these properties of brain function, it is much more feasible to multitask two high-level tasks if at least one of them is an automatic task.

Higher Level Versus Lower Level Tasks

Recent studies have investigated the combination of higher level tasks, which refers to tasks that require more mental computation (perhaps more complex computation) than lower-level tasks and which involve longer durations of processing, such as the comprehension of two simultaneously spoken sentences that take several seconds to utter. One important new element of this type of combination is that it often disallows task-switching (unlike most combinations of simple tasks). In this type of higher level dual-tasking, mental resources have to be shared between concurrent extended streams of thought. Many of the multitasks that are performed as part of actual job performance (as opposed to laboratory tasks) consist of two concurrent high-level tasks, as we describe here.

Effects of Training on Multitasking Performance

Some studies have found that, under certain circumstances, dual-tasking interference may be (p. 274) reduced or entirely eliminated. Dux et al. (2009) showed that training improved multitasking performance. Training was associated with improvement in multitasking and changes in brain activation that indicate faster, more efficient (less resource-consuming) processing by the brain.

Neural Efficiency

Neural efficiency can be defined in terms of the amount of brain resources consumed in performing a task to a given level of proficiency (Prat & Just, 2008). The consumption of brain resources can be measured in two related ways: (a) the volume of tissue that becomes activated above some threshold and (b) the mean activation level of a volume (Just, Carpenter, Keller, Eddy, & Thulborn, 1996). Typically, the two measures are correlated. Recently, brain imaging studies of higher level cognition in single tasks have found that high-skilled, high-performing individuals utilize fewer neural resources; that is, they show a smaller spatial extent or magnitude of activation (e.g., Newman, Carpenter, Varma, & Just, 2003; Prat, Keller, & Just, 2007; Reichle, Carpenter, & Just, 2000).

One brain property that underpins effective multitasking, much like skilled performance in other higher level tasks, is neural efficiency: high performers (or trained participants) show lower magnitudes and spatial extents of brain activation when compared to low performers in the same tasks. The role of neural efficiency has been identified in training studies for high-level cognitive tasks other than multitasking: it has been reported in studies of higher level visuospatial cognitive tasks (e.g., playing the game Tetris; Haier et al., 1992) and as a functional marker of individual differences between skilled and less-skilled readers (Prat & Just, 2010).

Higher levels of dual-task performance must ultimately be underpinned by higher levels of neural efficiency. Jaeggi and colleagues have shown that neural efficiency gains, in terms of a load-dependent decrease in activation of areas of the prefrontal cortex, underpin the ability some people have of maintaining higher levels of multitasking performance. Jaeggi et al. (2003; 2007) showed that the brain activation of high-performers decreased with increasing dual-task difficulty. Low-performing dual-taskers, in turn, showed a load-dependent increase in activation. For high-performers, the decrease was in a distributed network of areas that included lateral prefrontal areas (dorsolateral prefrontal cortex and the IFG). Again, brain imaging corroborates the importance of the executive network and strategic control for the processing of simultaneous tasks.

This finding indicates that, similar to other higher level cognitive tasks, high levels of performance in multitasking may be underpinned by neural efficiency; the use of fewer resources in areas of the prefrontal cortex, in turn, may be associated with the ability to automate task-specific dual-tasking processes (i.e., perform them without the benefit of frontal executive processes, such as listening to two people speak at the same time, without exerting strategic control). High-performers are thus able to maintain consistent levels of performance as task difficulty increases without exhausting their cognitive resources. For low-performers, the decrease in performance was associated with higher consumption of brain resources. The inability to maintain high levels of performance despite an increase in resource consumption suggests the selection of lower efficiency strategies (less effective algorithms) by low-performers. Jaeggi et al. (2007) postulates that in situations of cognitive overload, such as dual-tasking, efficient strategies include the ability to stay calm and focused on key elements of the task at hand. It is not unlike the expert gamer or pilot’s ability to maintain her focus on the relevant concurrent tasks (whose performance is also associated with less activation in comparison to novice gamers and pilots).

Brain Changes with Training

Training can lead to more efficient multitasking and reduce multitasking costs. The ability to deal with multiple inputs in cognitively stressful situations can be important in sectors such as aviation and the military. A seminal study of dual-tasking showed that after relatively modest amounts of practice some participants achieve virtually perfect time-sharing in the dual-task performance of two very simple tasks (Schumacher et al., 2001). Despite the improvement in dual-tasking performance following training, the authors raise fundamental questions about training and multitasking; namely, why do some, but not all, people achieve virtually perfect time sharing? In this section, we address these issues based on recent brain imaging studies and the application of video game playing training regimens.

Dux et al. (2009) showed that training in a dual task reduced the activation in an area of the prefrontal cortex, namely, the inferior frontal junction. The observation is consistent with the hypothesis that efficient multitasking results from a decreased reliance on brain regions involved in executive control. (p. 275) According to this hypothesis, general-purpose regions initially required to cope with novel task demands are, after training, progressively replaced by more efficient task-specific brain networks (Chein & Schneider, 2005; Haier et al., 1992). Dux et al. (2009) also reported that there were no areas whose activation increased after training. This indicates that training was associated with more efficient use of neural resources rather than recruitment of new cortical areas. Erickson et al. (2007) also showed a reduction in brain activation in most regions involved in dual-tasking after training. The decrease in activation was correlated with improvements in performance. A behavioral study showed that training can also improve dual-tasking in older adults. Bherer et al. (2005) showed that training improved dual-task performance in both older and younger adults. The improvement also generalized to novel task combinations.

Thus, what brain imaging has revealed so far is that the emergence of efficient multitasking does not necessitate the recruitment of new brain regions (Dux et al., 2009); rather, it may be associated with better synchronization or coordination between task-related areas and more efficient use of neural resources.

Video Game Training and Practice: Improvement in Selective Attention and Speed of Processing

Action video game playing can improve the ability to selectively attend to specific sources of information, and it can increase the speed of processing of visual information. In a multitasking environment such as air traffic control or piloting an airplane, the ability to increase the speed of skilled processes without trading away accuracy may be fundamental to avoiding a high-cost breakdown in performance.

Selective attention is one of the executive functions associated with the ability to maintain high levels of performance in multitasking environments such as action video games. Players have to learn how to rapidly adapt to variable task demands and selectively attend to the stimulus of interest (visual or auditory). In a series of studies of the effects of action video game playing, Bavelier and colleagues showed that habitual video game players, compared to non–video game players, have a marked advantage in visual selective attention, although they may be a self-selected group with some inherent advantage in visual processing (Green & Bavelier, 2003). In tasks where the player has to pick out a target that shows movement patterns different from other, similarly moving objects, habitual players are faster and more accurate. Active video game players of all ages make faster correct responses, thus freeing-up additional cognitive resources for other tasks that may immediately demand attention in a fast-paced environment (Dye, Green, & Bavelier, 2009).

The positive effects of video game training transfer to nongaming environments as well. Bavelier and colleagues argued that perhaps the most interesting implication of action video games is their possible application in educational games. The rich perceptual structure, emotional content, and positive experience inherent in video games may be harnessed in the service of academic or vocational learning. In contrast to video action games, many educational games focus on creating practice opportunities for students; but what these educational games provide in terms of practice, they usually lack in interactivity and stimulation of student interest (Bavelier, Green, & Dye, 2010).

Further investigation of the use of video gaming as a training regimen for dual-tasking improvements may help to reveal the brain bases of training effects in multitasking, multistimuli environments. The attractive and positive features of video gaming, with its inherent multitasking, may provide a foundation for developing new instructional techniques.

Brain Bases of Improvement: What Changes After Multitask Training?

Bavelier et al. (2011) identified the neural bases of improved selective attention in action video game players, indicating which processes became more efficient. As distracters and attentional demands increased, skilled gamers showed less activation of visual areas and of a frontal-parietal network of areas (superior frontal sulcus, middle frontal gyrus, IFG, cingulum, and intraparietal sulcus) in comparison to nongamers. Because gamers recruit fewer cortical resources (showed greater neural efficiency) during game playing (without trading away accuracy), the authors argue that gamers are able to free up additional processing resources (Bavelier et al., 2011). The increased neural efficiency of gamers was associated with more effective pattern recognition and executive skills across a range of tasks.

At the beginning of the chapter, we loosely compared pilots and digital natives in their ability to multitask. Interestingly, cognitive neuroscience has shown that the brain bases of skilled performance in these two groups are not so different: both experienced pilots and trained/experienced gamers show (p. 276) evidence of greater neural efficiency when operating simulated aviation tasks and playing first-person action games, respectively. Bavelier et al. (2011), as just discussed, showed that as task attentional demands increased, skilled gamers showed less activation in a network of task-related areas (superior frontal sulcus, middle frontal gyrus, IFG, cingulum, and intraparietal sulcus) in comparison to nongamers. Peres et al. (2000), in a study of novice and experienced pilots, showed that with increasing task difficulty (increasing airspeed), expert pilots showed reduced activity in visual and motor centers of the brain. The decrease in activity contrasted with predominant activation of the frontal and prefrontal cortices. Novice pilots, by contrast, showed widespread increased activation of anterior and posterior brain structures (visual, parietal, and motor cortices as task difficulty increased). Whereas skilled pilots efficiently recruited brain areas involved in processes pertinent to dealing with the increase in task difficulty (visual working memory, selective attention, and decision making), novice pilots showed a general increase in brain activation that suggests less effective allocation of mental resources. Because experienced gamers and pilots recruit fewer cortical resources during the game playing and operation of a simulator, the authors argue that these experienced participants were are able to free up additional processing resources (Bavelier et al., 2011). Skilled pilots and experienced gamers alike are more efficient in their use of cortical resources.

In sum, video game playing may be an effective training regimen for improving cognitive skills such as selective attention and speed of processing that are important for maintaining high levels of performance in sensorimotor multitasking.

Individual Differences: Why Are Some People Better at Multitasking than Others?

Individual differences in the ability to multitask must be underpinned by differences in brain function. Interestingly, working memory capacity, one of the better predictive indices of individual differences in high-level cognition, is not very predictive of dual-tasking performance. Previous studies showed that individual differences in working memory capacity were not correlated with individual differences in multitasking performance (Jaeggi et al., 2007). Buchweitz et al. (2012) showed that the group of individuals who could perform a higher level dual task included both lower and higher reading span participants. Individual differences in working memory capacity also did not predict dual-tasking performance in the study, consistent with the findings of Jaeggi and colleagues. However, the lower span multitaskers showed a greater increase in synchronization than did higher span multitaskers in the network of brain areas associated with the task (Buchweitz et al., 2012).

As described, Buchweitz et al. (2012) reported increased frontal-temporal synchronization of brain activity in multitasking (relative to performing the single tasks). The study drew on a pool of university students who could successfully listen to two people at the same time and answer questions about what they just heard (without a decrement in comprehension performance in comparison to listening to just one person). The ability to maintain high levels in dual-tasking performance was associated with a shift of the timing of the activation in Broca’s area in dual-tasking, and there was a systematic difference between higher and lower level working memory individuals in their amount of shift of the activation. The participants with lower working memory capacity for language displayed the larger shifts in brain activation, which may be a brain marker of adaptation to the difficulty of the task by lower working memory capacity participants who are able to multitask.

Jaeggi et al. (2007) showed that high-performers were able to more efficiently draw on cortical resources than low-performers. High-performers showed less activation than low-performers in a network of brain areas associated with the dual task. The network of areas in which there were significant activation changes associated with improved performance included areas that may be associated with executive processes (left dorsolateral prefrontal cortex, superior frontal sulcus) and with more task-related processes (IFG, inferior and superior temporal sulcus). The authors interpreted the association between less brain activation and high levels of performance as suggestive of differential neural efficiency, resulting in a state of calmness and focused attention in the situation of mental overload (Jaeggi et al., 2007). Recent studies of higher level cognitive processes have also shown that higher skilled individuals tend to recruit fewer neural resources than do lower skilled individuals (e.g., Haier et al., 1988; 1992; Newman et al., 2003; Prat & Just, 2010).

In summary, early findings suggest that two types of brain changes seem to underlie individual differences and training effects in multitasking. There is an *increase in synchronization (relative to the single task) between the task-related brain areas*. The successful participants showed a change in the (p. 277) temporal organization of their neural processing, a shift in the timing relation among nodes in the language network, thus achieving higher functional connectivity in the dual-task condition. Moreover, successful participants with lower working memory capacities showed larger time shifts. It seems that the timing of the frontal lobe is adaptive in situations of increasing task demands due to concurrent processing. A second brain change associated with successful multitasking was *higher neural efficiency*, as reported by Jaeggi and colleagues. Together, these brain changes begin to hint at the individual differences in brain activation for successful multitasking: multitasking requires faster, better synchronized, and less resource-intensive processing.

Multitasking with Two Simple Tasks: Brain Imaging Insights

Multitasking with Two Simple Reaction-Time Tasks

Studies of simple multitasking often present the stimuli from the two simple tasks in two different modalities and are very amenable to task-switching by rapidly switching attention from a completed item in one modality to the next item on the queue in the other modality, and so on. One of the most frequent paradigms employed is the concurrent processing of visual discrimination (object or luminance) and auditory discrimination (e.g., different tones), with each stimulus to be followed by its own type of response in each component task (say, a vocal response for the visual task and button press for the auditory task). The finding of such simple dual-tasking studies is that performance in each of two concurrently performed simple tasks is usually slower than the performance in either of the single tasks. The generally proposed account for such multitasking studies with simple tasks is that the decrement in performance in these tasks may be associated with interference between the tasks. The label “interference” is imprecise insofar as it does not specify the psychological mechanisms nor the neural substrate involved in the interference.

Brain Bases of Interference in Simple Reaction Time Dual-Tasking

The concept of a central processing bottleneck limiting the ability to multitask first arose long before the advent of brain imaging and can now be addressed with fMRI studies. It is now evident that the neural substrate of a central bottleneck is not a single entity. The central bottleneck is the result of competition for resources in a set of cortical processing centers; the competition arises because of the processing capacity limitations within each center, as well as the limitation on intercenter communication.

The neural substrate of the central bottleneck of dual-task processing typically includes the lateral frontal, prefrontal, dorsal premotor, anterior cingulate, and intraparietal cortex (Dux, Ivanoff, Asplund, & Marois, 2006). But the precise constituency of a central bottleneck depends on the precise nature of the two tasks. Among these centers, the lateral prefrontal cortex appears to be more of a central bottleneck than the other network components. This conclusion stems from the finding that performance decrements and performance enhancement associated with training are associated with modulations of the activation level of the lateral prefrontal cortex (e.g., Dux et al., 2006; 2009). This region is associated with mapping (translation) from sensory inputs to motor outputs and includes a central stage of processing that precedes decision making and response selection (Dux et al., 2006; 2009; Marois & Ivanoff, 2005).

The study of Schubert and Szameitat (2003) suggested a dissociation of activation increases due to interference among more central processes versus motor processes in simple dual reaction time tasks. The interference within more central processes, such as attention shifting, preparation of competing task sets, and preparation of potentially interfering processes, was associated with activation increases in the inferior frontal sulcus. The interference within motor processes was associated with the activation increases in the precentral sulcus and the presupplementary motor area.

Brain imaging studies can usually identify the brain locations involved in the multitasking effects (performance degradation), and they can sometimes indicate what psychological processes are involved. But *interference* remains a label for a phenomenon without much explanation of the underlying mechanism. Similarly, attributing an effect to a *central bottleneck* simply rules out mechanisms at the sensory and motor levels, without specifying any particular central mechanisms.

Meyer and Kieras (1997) demonstrated that with extended practice, the response times can be as fast in a dual task as in each of the two very simple tasks. In another study by the same group, interference between the two tasks was modulated by instructions about task priorities and skill level (Schumacher et al., 2001). Meyer and Kieras proposed that, with practice and instruction, executive **(p. 278)** control processes can organize simple dual-task processing in a manner that eliminates any performance costs. The neural implementation of their processing account may resemble some of the training effects of extended multitasking practice described earlier.

To summarize, brain imaging studies have identified cortical centers onto which simultaneous processes in dual-tasking, such as response selection, may converge. The magnitude of activation and the timing of activation in these frontal centers can be modulated by training (Dux et al., 2009). Although the underlying processes responsible for a decrement in dual simple reaction time tasks may not be entirely clear, brain imaging has revealed the neural substrates involved in such tasks.

Future Directions: The Neural Circuitry of the Multitasking Generation

Future research will undoubtedly continue to explore the neurodevelopmental mechanisms of a young multitasking generation of “digital natives” (Prensky, 2001). The human brain is fairly unchanged over thousands of years in terms of its biology, but its cognitive capabilities continue to expand. Reading written language is an example of a recent capability of the human brain, made possible because human culture and its educational institutions can induce new brain capabilities and propagate them over large expanses of time and parts of the globe. It would not be surprising to find that multitasking ability increases broadly throughout the population in an electronic age. The central scientific challenge is to further understand the brain mechanisms that both enable and constrain multitasking and to use this understanding to enhance learning and performance in educational, workplace, and recreational contexts.

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