

What brain imaging reveals about the nature of multitasking

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Abstract

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 considering the brain activation patterns observed in multitasking as opposed to single tasking, it is possible to observe what is distinctive about multitasking.

The account goes beyond relating multitasking to specific brain areas. It describes the functioning of a large scale cortical network whose constituency and organization is determined by the multitasking. This approach enables accounts of new phenomena, such as multitasking with high-level cognitive tasks, as well new accounts of old phenomena, such as interference effects between two simple tasks being performed concurrently. The cognitive neuroscience approach also raises and answers new questions, such as what distinguishes better from poorer multitaskers, and what brain changes occur after multitasking training. We conclude that brain imaging studies will continue to help understand how to train both young and old brains to deal with an increasingly multistream world.

Keywords:

Multitasking; Cognitive Neuroscience; Digital Natives; Neurocognitive Perspective; fMRI; Neural Mechanisms; Individual Differences; Training; Executive Functions; Automaticity.

Multitasking is as old as mankind, simply because life is often a multitask. 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 had to attend to one or more children and simultaneously perform other basic survival tasks. 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.

What is not as old as mankind is the 21st century technology that provides a myriad of information streams on various communication devices, multiplying the already multiple streams of available information that might potentially be attended 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.

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 is a complex cognitive process that 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 while sharing at least some common infrastructure. The scientific questions concern the nature of the co-occurrence: 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? Are there gender differences? 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.

The term *multitasking* is sometimes used informally to refer to simultaneous interaction with different media and tasks, such as watching a movie while interacting online and doing school homework, where task performance is only loosely assessed. In this chapter we will use the terms *multitasking* and *dual-tasking* (interchangeably) to refer to the concurrent *performance* of two or more cognitive tasks. Where applicable, we will try to distinguish true maintenance of two concurrent streams of thought versus rapid switching between two tasks.

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 into the extraordinary ability of processing 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. Will a new cohort of young multitaskers raised with multi-stream information technologies be more proficient at multitasking than their predecessors? Are their brains different, either anatomically or functionally? In this chapter we will draw on recent noninvasive brain imaging research on multitasking to attempt to answer some of the questions posed above. In particular, we will address these specific questions: (1) What limits the ability to multitask? (2) Can we train our brains to better perform multiple, concurrent tasks? (3) Are there individual differences in the brains of successful multitaskers? And a question about the future: (4) Are new neural capabilities being developed in young minds born into multitasking, multi-stimulating social environments?

The ubiquity of technologically-based information streams, such as mobile phones, 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 addressed. Multitasking in technological environments used to be 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-and-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 multitasking abilities in the rest of us. There is currently a generation of people who have 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 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 type of new media multitasking (loosely defined) is the playing of contemporary first-person action videogames. Players must simultaneously process a myriad of visual information, command a videogame 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 videogame 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 processing (Green & Bavelier, 2003; Dye, Green & Bavelier, 2009). Can this ability be improved in non-gamers by extensively training them? The answer seems to be yes. With as little as 1 hour of video-game playing per day for 10 consecutive days, participants with minimal previous videogame experience showed expansion of their field-of-view and in the ability to detect visual stimuli presented in rapid succession (Green & Bavelier, 2003).

Like the earlier issues raised above, these issues can now be addressed in terms of their neural substrates. We can now investigate what occurs in the neural bases that underpin the remarkable ability to multitask and maintain good performance. 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.

The neurocognitive perspective: a conception of brain function underpinning cognitive tasks

The goal of this chapter is to present the contribution of cognitive neuroscience to the understanding of multitasking. Using the new knowledge of 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 mental resources than 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. In previous decades, human thinking was believed to be the product of a monolithic engine of thought, and that this engine was separable from motor and sensory systems. Brain imaging has made it very clear that thought is anything but monolithic. 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 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, aside from sensory and motor ones.

The second major change in the way cognition is construed as a result of brain imaging findings is that the motor and sensory brain centers have been revealed to be part of the same large-scale network as the “cognitive” centers, and they are not separable, in that they closely interact with and mutually influence the cognitive centers.

The main evidence of the extensive collaboration between brain centers (previously construed as the interaction between processes) is that the activation among various subsets of the participating centers is synchronized; the activity levels of the synchronized centers rises and falls 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 et al., 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 the 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 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.
5. Resource consumption (indexed by amount of brain activation) is modulated by cognitive workload. The more demanding the task is, the greater the amount of activation in one or more areas.
6. The sensory and motor centers are tightly integrated with the “cognitive” centers and are not just peripheral buffers, as they were previously construed. The synchronization between sensorimotor centers and cognitive centers in multitasking provides evidence of this integration.

The accompanying figure 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, where 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

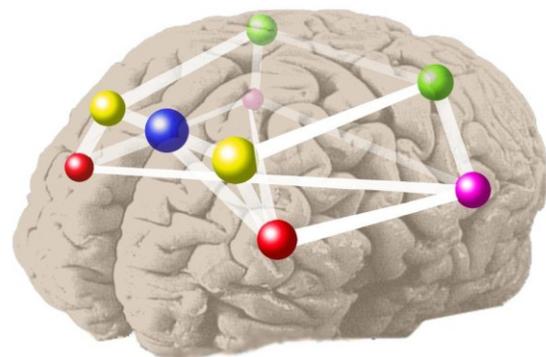


Figure 1. Schematic depiction of a large-scale cortical network with the network nodes communicating via white matter tracts.

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 than just 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 hence could compete for common resources. It is the combinatorial chemistry 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. 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.

Applying a neurocognitive perspective to multitasking

Brain imaging has afforded two new ways of understanding dual-tasking limitations. One is associated with the brain's inter-node communication capacities, and the other with the total brain work limitations. These biologically-based accounts of the limitation to perform simultaneous tasks are discussed in turn.

The discovery that cognition was a network function rather than a monolithic system exposed a new resource that could constrain multitasking, namely the communication resources that allow the various brain centers to communicate with each other. Inter-process 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 the 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 specific 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. It may be the case 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. 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 below.

Bandwidth limitations. Bandwidth refers to the maximal rate of data transfer supported by a communication channel (Shannon, 1949). The concept of bandwidth limitations may apply in special neurological populations. For example, a current theory of autism proposes that the cortical communication bandwidth between frontal and posterior cortical areas is lowered in autism (Just et al., 2004; 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 (Garcia-Villamizar & 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 because the information flow from the two tasks combined may be greater than the bandwidth that the communication channels can support.

To our knowledge, there are no existing 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. But one fMRI study found a neural function that changed during high-level multitasking and that may be associated with the brain's communication capabilities.

This study examined the multitasking of two complex but highly automatic tasks of 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 just 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 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 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 sec) 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 sec. 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); more effective communication between the 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. It was the participants with lower working memory capacity for language who 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.

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). The authors suggest that the increase in synchronization between the specialized networks in the dual task (left dorsal inferior frontal gyrus and superior parietal lobule) reflects greater and more complex demands being placed on the system.

Limitations on total activation (total brain work). It is obvious that there is an upper limit on how much thought can occur at any given time, a limit on one's total processing capacity. High level multitasking would surely exceed this limit in some cases, as the decrements in dual task performance (relative to single task performance) suggest. Brain imaging has suggested a simple account of higher-level dual-tasking limitations: there may be an upper limit on the amount of activation that can be

recruited 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 of the brain, then perfect additivity of the two tasks might be expected to activate $x+y$ voxels. But that is not what happens. Typically performing both tasks simultaneously 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.

An interesting range of other high-level tasks has also been examined with fMRI research: driving while listening to someone speak (Just et al., 2008), performing mental rotation while listening to someone speak (Just et al., 2001; Just et al., 2008; Newman et al., 2007), listening to two people speak at the same time (Buchweitz et al., 2012), and performing dual n -back tasks (Jaeggi et al., 2007). A decrease in activation of the task-related network (left fusiform gyrus and middle temporal gyrus) was also reported in a language dual tasking paradigm (Kana pick-out test) which involves simultaneous sentence comprehension and vowel identification (Mizuno et al., 2012).

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.

Cell phone use during driving. One of the real-world multitasking concerns involves the use of a cell phone during other activities, such as 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 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 a simultaneous 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 they are 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. The accompanying figure graphically depicts how listening to someone speak decreases the driving-related activation. This 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 more to hands-free cell phone use.

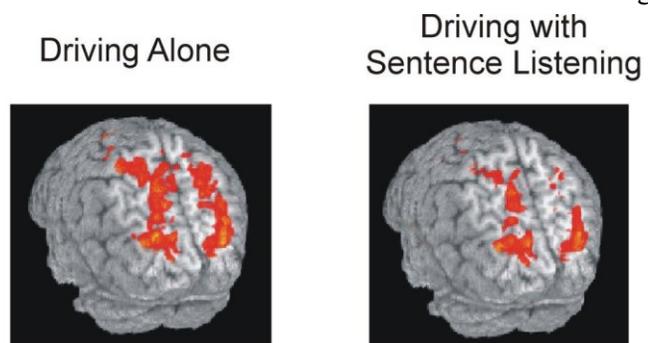


Figure 2. The brain activity associated with driving decreases by 37% when the driver is also listening to someone speak.

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, to dial a number, or to 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 et al., 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 commonsense reasons, but because of the compromised multitasking performance imposed by cognitive and neural constraints.

Effects of task automaticity

An important factor to consider in multitasking is whether one or both of the two tasks can be performed automatically as opposed to being performed under strategic control. When automaticity was 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 non-automatic task could not be co-performed (Schneider and Shiffrin, 1977).

When fMRI brain imaging became available, a more satisfying account of automaticity emerged. The more 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.

In practice, it is difficult to experimentally assess the effects of automaticity. It takes several hours of practice for a task to become automatic (especially higher-level tasks), so any experimental study of automaticity effects on multitasking would have to invest those many hours in training participants. Automatic tasks become automatic either as a result of deliberate training (Schneider & Shiffrin, 1977) or extensive natural experience (e.g. listening comprehension). It is known to be very difficult to perform two non-automatic tasks concurrently. In theory, it should be possible to first practice participants in one or both tasks until they became automatic, and then the probability of being able to perform them concurrently while maintaining reasonable levels of accuracy should increase.

Extensive practice is an essential ingredient for achieving automaticity, for two main reasons. First, the many component processes can become more efficient with practice, so that they consume fewer

resources. We know that they consume fewer resources because the amount of activation in many brain areas decreases with extensive practice. A study of simple reaction-time dual tasking has shown precisely this effect. Training (and possibly increased automaticity of the lower level tasks) was associated with improved performance and a decrease in dual-task related activation (Dux et al., 2009). The decrease in dual-task related activation may have followed from increased automaticity. Specifically, the left inferior frontal junction showed a significant reduction in the activity difference in comparison to the single tasks in the comparisons between pre-, mid-, and post-training sessions; by the final training session there was no significant difference between the activation in that area for the dual- and single-task trials (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. For example, as a participant gains experience in a novel complex task like the *n*-back task, the degree of strategic control may decrease, making it more feasible that it can be performed concurrently with another task.

Multitasking with higher 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.

The striking finding in laboratory studies is that even college undergraduates, who by virtue of their age and experience in computer use should be among the most effective multitaskers, are often unable to perform two complex tasks concurrently while maintaining reasonable accuracy. Of course, almost anyone can listen to music while performing a non-demanding 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). 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 actually performing two high-level tasks at the same time is something that many people cannot do.

Unlike a dual task that requires comprehension of two simultaneously spoken sentences, the combination of a mental rotation task (of visually-depicted 3D objects) and a listening comprehension task draws on two rather different sets of brain resources. The latter two tasks are underpinned by relatively independent brain networks. This combination of tasks is also different from driving and listening in that mental rotation is a non-automatic, controlled task whereas driving (by an experienced driver) is automatic. Studies have shown that mental rotation, performed concurrently with listening comprehension, draws mental resources away from the language processing regions, and vice versa. The activation of both networks involved in the task decreased from single to dual-tasking (Just et al., 2001). The dual-task performance decrements in studies of higher-level multitasking suggest a biological constraint on the amount of mental resources (in terms of volume and magnitude of activation) that can be distributed across networks of the brain. Even though listening comprehension is a highly automatic task, if it is performed in combination with another task, which can be either automatic or nonautomatic, there is a limitation in the brain resources that can be divided up between listening comprehension and the other task.

In sum, the studies of higher-level multitasking suggest an identifiable upper limit on the total processing capacity (brain work) of the human brain, especially in studies that combine dissimilar tasks. The studies that combine dissimilar tasks with spatially-distinct brain networks provide a quantifiable measure of the relative decrease in activation from single to dual-tasking.

Multitasking with two simple reaction-time tasks

The finding of most dual-tasking studies with simple reaction time tasks is that there is a decrement in performance in comparison to single tasks. Performance in each of two concurrently performed simple reaction time (SRT) tasks is usually slower than the performance in either of the single tasks. These lower-level (sensorimotor) tasks, such as responding to the location of a light, involve fast, usually sensory-related (typically visual or auditory) processes. The tasks are also amenable to task-switching during the processing of the stimuli by rapidly switching from a completed item in one modality to the next item on the queue in the other modality, and so on. Each stimulus is typically presented in less than one second.

The paradigm of dual-tasking with simple tasks is easily amenable to stimulus onset asynchrony manipulations; it also allows for decomposition of the processes involved (for example, different sensory detection processes; motor response selection processes). One of the most frequent paradigms employed is the concurrent processing of visual (object or luminance discrimination) and auditory (e.g. different tones) stimuli. These dual-tasks sometimes also require different types of response to each component task (say, vocal response for the visual task and button press for the auditory task) (D'Esposito et al., 1995; Stelzel et al., 2006).

One of the seminal fMRI studies of simple reaction time dual tasking investigated an auditory and a visual three-choice task which were performed either separately as single tasks or concurrently as dual tasks (Szameitat et al., 2002). In the dual-task condition, two stimuli (one from each task) were presented in rapid succession to allow for interference between the component tasks. This paradigm is a clear example of the methodological rationale behind the choice of simple reaction time tasks for the investigation of dual-tasking, and the ease with which the task can be decomposed into processing components (e.g. sensory processing, decision, and response generation). Other examples include Dux et al. (2006), who investigated a dual auditory and visual discrimination task (eight tones, man-made or natural sounds; circles with different colors); Dux et al. (2009), also a visual and auditory discrimination task (discriminate between two faces; auditory task: same as Dux et al. (2006)); Sigman and Dehaene (2006; 2008), a number and tone comparison dual-task (number greater than or less than 45; high or low tones); Klingberg (1998), a visual (luminance) and auditory discrimination task (tone) with 1-second SOA; and Jiang (2004), a color and shape discrimination dual-task. The main contributions emerging from these studies are discussed in turn.

Before the advent of brain imaging, various accounts were proposed to explain the decrements in performance associated with such dual-tasking. One of the main factors postulated as the cause of decrements in dual task performance is *interference*. The interference may be at the level of various processes, such as detecting the stimuli associated with each of the tasks or making the response, or both. Interference is measured mainly in terms of response delay effects but also in terms of accuracy of response. Interference limits dual-tasking when there are competing sensory-perceptual processes and cognitive processes shared between the concurrent tasks (Pashler, 1994). The degree of interference is modulated by a number of variables, particularly the degree of temporal overlap between tasks, the amount of practice (skilled performance), the modality incompatibility of stimulus-response pairs, and by modality incompatibility between stimuli (also called cross-talk). It has been suggested that dual-task interference and processing limitations are probably not likely to be attributable to modality differences, i.e., cross-talk (Pashler, 1994). For example, the PRP effect (Psychological Refractory Period, the time interval during which the response to a second stimulus is slowed because a preceding stimulus is still being processed), has been found regardless of modality of the stimuli.

Studies show that in simple reaction time dual tasks (for example, pressing a button when a circle appears and when a tone is played), there is competition for what is identified as central cognitive processing resources. Two cognitive tasks may draw on and compete for a common central cognitive processing resource, implemented as a specific network of the brain (usually associated with areas of the prefrontal cortex) that may be a bottleneck. When two responses have to be produced, response selection and production compete for motor, premotor, and planning center resources. When two very simple reaction-time tasks are being performed concurrently (or with short stimulus onset asynchrony, SOA), the acts of selecting and generating a response in the two component tasks may interfere with each other. The dual-tasking limitation in processes that are shared between competing tasks would be imposed by a limited-capacity response buffer. Presumably this is a central bottleneck for competing response selection processes.

The competing processes involved in response selection are different from those involved in a peripheral bottleneck of motor execution or perceptual attention. The mapping of a stimulus in a dual task to a response precedes the execution of the response (Jiang, 2004). The mapping of the response would thus be the process where the competition for resources results in a bottleneck. Perceptual attention can be divided between more than one perceptual object (e.g. Pylyshyn & Storm, 1988). Therefore, this type of central bottleneck is based on the assumption that response selection processes can be allocated to only one task at a time (Jiang, 2004).

Meyer and Kieras (1997) disagreed with the idea of dual tasking with two very simple tasks being limited by a central bottleneck. They noted that parallel processing (or perfect time sharing) between two competing tasks can be achieved with practice. In another study by the same group, it was shown that interference between the two tasks in a dual task can be modulated by instructions about task priorities and skill (Schumacher et al., 2001). In this sense, as dual-taskers develop the skill of performing simultaneous tasks, they also develop the ability to exert strategic control over the task (executive processes); strategic control of the queuing of response enables parallel processing of competing tasks. The dual-task interference that stems from dual response selection and production in simple reaction dual tasks can be virtually eliminated if multitaskers adopt a strategic approach to the task.

To account for such findings, Meyer and Kieras (1997) proposed a model of adaptive executive control (AEC) for dual-tasking without a central bottleneck. The model attributes initial dual tasking costs to poor coordination of the two tasks, a limitation that can be eliminated with adaptive executive control. These findings show that executive functions play a key role in the performance of even simple multitasks. The findings also suggest that the cost of dual tasking in simple reaction tasks may be largely offset by training and by adopting specific strategies that involve strategic control (for example, prioritizing the order of task execution).

The brain bases of interference in simple reaction time dual-tasking

The concept of a central bottleneck of processing and the phenomenological experience that it is difficult to pursue two streams of thought concurrently arose in early behavioral studies. Although the concept first arose before the advent of brain imaging, fMRI studies can now identify the neural substrate of a central bottleneck, but it is not a single entity. The central bottleneck is the result of competition for resources in a cortical network of association areas; the competition arises because of the processing capacity limitations within each center as well as the limitation on intercenter communication.

Multitasking is underpinned by two networks of association brain areas (associated with each of the two tasks) whose precise constituencies depend on the nature of the two tasks. The assumption underlying the general concept of a central bottleneck is that there is a stage of cognitive processing that is common to the two tasks and that this central processing of the two tasks cannot be performed concurrently without some performance penalty (in simple reaction time dual tasks, this stage is the response selection). In the following sections, we will describe the neural resources identified by brain imaging studies that are most commonly associated with a bottleneck of central processing in the simple dual tasks, and how extensive training affects the processing of this network.

The neural substrate of the central bottleneck of dual-task processing includes the lateral frontal, prefrontal, dorsal premotor, anterior cingulate, and intraparietal cortex (Dux et al., 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 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 of the lateral prefrontal cortex (e.g. Dux et al., 2006; 2009). This set of areas is associated with mapping (translation) from sensory inputs to motor outputs and with a central stage of processing that precedes decision-making and response selection (Dux et al., 2006; 2009; Marois & Ivanoff, 2005). Sensory-motor translation refers to processing information at the sensory level (for example, auditory and visual stimuli in the dual task) and mapping that information to a response, which involves motor processes such as pressing a button or vocalizing.

The neural substrate of performance decrements (interference) in simple reaction time dual tasks

One of the issues investigated by brain imaging studies is the degree to which the decrements in performance in simple tasks reflects a limitation in the ability to concurrently select two responses versus the engagement of executive functions and strategies to optimize performance (Marois & Ivanoff, 2005). A brain imaging study of PRP investigated how the activation in areas of the executive network (the dorsolateral and ventrolateral prefrontal cortices, the anterior cingulate cortex, and the pre-supplementary motor area) was modulated by the variation in stimulus onset asynchrony (SOA) (Jiang, Saxe, & Kanwisher, 2004). The hypothesis was that if executive processes were engaged to a greater extent in shorter versus longer SOA conditions, then there should be more activation of this executive network with shorter SOAs. However, the results showed no increase in activation in these executive areas with shorter SOA. Instead, the increase was found in regions of the right inferior frontal lobe (Jiang, Saxe, & Kanwisher, 2004). Similarly, Herath et al. (2001) reported that activation of the right inferior frontal gyrus (RIFG), near the precentral sulcus, was associated with interference in a shorter interstimulus interval (ISI) condition in comparison with a longer ISI. The activation of RIFG was modulated by shortening the ISI between the component tasks. In other words, the closer in time the presentation of the two stimuli from the two component tasks, the more the response selection processes interfere with one another and the greater the recruitment of cortical resources in right prefrontal cortex (RIFG). There appears to be a processing center in the right prefrontal cortex areas recruited in response to increasing dual-task coordination demands. Recruitment of the RIFG in such simple reaction time dual-tasking may represent a spillover of processing (and hence activation) from left-hemisphere prefrontal areas. The increased activation in RIFG near the precentral sulcus may be associated with additional recruitment of resources for the dual-task in comparison with the single task.

Whatever the mechanism that is responsible for the interference between tasks, it appears to be amenable to instruction. Schubert & Szameitat (2003) investigated the effects of varied SOAs (50, 125, and 200ms) in the dual task and asked participants to respond to the tasks in the order they were presented [similar to Meyer & Kieras (1997) described above]. The instruction to respond to the two tasks observing the order of their respective stimulus presentations may have eliminated the decrement in performance associated with interference between response selection processes in dual-task performance (Schubert & Szameitat, 2003). The competing or interfering process was seemingly eliminated once participants strategically focused on processing and responding to each component task in a given order. Similarly, in a behavioral study, Schumacher et al. (2001) also found that interference between tasks can be modulated by instructions about task priorities.

The precise mechanism involved in interference is not clear, but, as discussed earlier, it may involve a process of mapping stimuli to the responses. While some studies associated the activation of the right prefrontal cortex areas with increasing dual-task interference, Schubert & Szameitat (2003) found more activation in dual-tasking than single tasking in a network of prefrontal, temporal and parietal areas. They were able to dissociate central interference (response selection) from interference due to motor processes. Activation of the inferior frontal sulcus, rather than RIFG as reported by Herath et al. (2001), has been associated with processes managing central coordination. Motor interference and response

competition are presumed to be managed by processes associated with the precentral sulcus and the pre-supplementary motor area (Schubert & Szameitat, 2003).

Szameitat et al. (2002) used two different methods of analysis (cognitive subtraction and parametric manipulation) to reveal that there was more dual-tasking-specific activation in a network of cortical areas along the inferior frontal sulcus (IFS), the middle frontal gyrus (MFG), and the intraparietal sulcus (IPS) in comparison with single-task performance. It remains unclear, however, whether activation of IFS is associated with amodal, executive processes.

In this sense, another possible source of the performance degradation in simple reaction time dual tasks may stem from the modality incompatibility of stimulus-response pairs. For example, it seems easier to respond to a spoken question by speaking than by writing. An example of modality compatible stimulus-response pairs are visual stimulus–manual response and auditory stimulus–vocal response; the corresponding modality-incompatible pairs are visual–vocal and auditory–manual (Stelzel et al., 2006). Incompatibility between stimulus and response has been shown to affect performance in terms of significantly higher dual-tasking costs in comparison to compatible pairings (e.g. Levy & Pashler, 2001).

Brain imaging research has shed some new light onto the issue of modality incompatibility effects, at least in terms of which brain areas are involved. More activation of prefrontal areas, including the left inferior frontal sulcus, has been associated with modality-*incompatible* dual-tasks in comparison with modality-*compatible* dual-tasks (Stelzel et al., 2006). The result indicates that modality-incompatibility evokes additional processes associated with the left inferior frontal sulcus (IFS); however, the brain imaging findings do not greatly illuminate which additional processes are being evoked by modality incompatibility. More activation of the left IFS has also been observed in studies of the Psychological Refractory Period (PRP) (Szameitat et al., 2002; 2006). This finding implicates the left IFS in the interference caused by temporal conflict (PRP) and stimulus-response compatibility effects of dual-tasking. In sum, studies show the L IFS may be involved in a mechanism of coordination (management) of competing response selection and mapping processes between tasks (Stelzel et al., 2006). Additionally, the lateral frontal, prefrontal, dorsal premotor, anterior cingulate and parietal cortices have been proposed as the neural substrates modulated by dual-tasking interference in simple reaction tasks (Dux et al., 2006). The areas are considered to constitute a strategic control network (Chein & Schneider, 2005).

So the new insights provided by brain imaging regarding performance degradation in dual versus single simple response time tasks suggest that 1) the computational capabilities of areas of dual-task-specific activation (the left IFS or the RIFG) may underpin the limitations of processing and responding to two tasks at the same time; 2) the competition for central processing resources in simple reaction tasks may be underpinned by a competition for inferior frontal lobe resources; 3) the degree of interference and the degree of activation of the dual-task specific areas are amenable to task instruction and training.

The unresolved issue is whether the interference is at the level of central cognitive processes (active monitoring of the tasks) or at the level of response selection (passive queuing). fMRI studies do show, as discussed above, that these processes can be dissociated at the cortical level. These conclusions indicate what “interference” may refer to. Although it was not incorrect to refer to these multitasking effects as interference, it is more precise to say that there are specific dual-task related processes (such as executive functions or response selection) that are engaged at the same time and, thus, consume more cortical resources. What was understood as interference may be reconstrued or further characterized as specific processes that co-occur in dual tasking that compete for limited neural resources that cannot be simply divided up between two tasks. The label “interference” may be imprecise in that it does not describe the actual mechanism that affects dual-tasking performance in terms of recruitment of cortical resources (see the discussion about spatially distinct networks in higher-level dual-tasking).

Although the accounts above contribute to the understanding of multitasking, they seem lacking in terms of contemporary standards. As we have seen, the brain imaging studies usually can 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.

The brain imaging studies showing an increase in speed of processing associated with training (Dux et al., 2009) indicate a *central* mechanism for the bottleneck. The processes that constrain the dual-task performance are not peripheral, or sensory-related; rather, they involve a central processing of information (say, mapping from sensory signal to motor response) that is common to the component tasks (that is, it is required by both tasks in the dual tasks). The central process that limits simple reaction dual tasking receives input from earlier processes. For example, after the sensory information has been processed, a more central process may select which button to press, given the sensory information. Dux and colleagues (2009) reported that the time at which activation in the inferior frontal junction (IFJ) occurs gradually decreases, or speeds up, with training. Their results showed that with training, the peak of the IFJ activation in the dual task occurs earlier than before training, a phenomenon which they referred to as an increase in speed of processing. Dux and colleagues argue that the increase in the latency of processing of this cortical center (IFJ) indicates that there is a central bottleneck. In other words, if performance improvement due to training was associated with faster processing by the IFJ, this area may well be a node (of the network recruited for the dual task) where processes converge and whose resources are limited when shared by two tasks.

Executive function in simple-reaction dual-tasks. Accounting for multitasking effects in terms of executive processes provides some opportunity for an advance, in two ways. First, it is a process account, of a specific mechanism that coordinates the concurrent execution of two tasks. Second, executive processes are strongly associated with a particular set of brain locations (Chein & Schneider, 2005).

Executive functions involve processes that help organize goal-directed actions. These functions are fundamental for those dual-tasks that involve switching attention between the two tasks. Maintaining the coherence and temporal organization of goal-directed actions is underpinned by prefrontal cortex function. The organization of actions in time (the most general characteristic of prefrontal functions) depends on prefrontal cortex (PFC) function (Fuster, 2008). Studies of brain imaging that investigate the central bottleneck of processing consistently associate the management of dual-tasking processes with areas of the prefrontal cortex.

In simple reaction time multitasking, activation of the executive network is associated with directing attention and maintaining information. The network is engaged especially in dual-tasking paradigms that involve non-automatic tasks and paradigms that are amenable to task-switching. Interfering processes between the component tasks may be the main cause for the need of executive processes to resolve conflicts in dual-tasking performance (Szameitat et al., 2002).

It is important to note that not all dual-tasks require the engagement of executive functions. Activation of executive-network related areas, such as the dorsolateral prefrontal cortex (DLPFC) were absent in several studies of high-level multitasking (Buchweitz et al., 2012; Just et al., 2001; 2008; Newman et al., 2007). The consistent finding of a *lack* of activation of executive-network related areas of the brain is suggestive that the tasks were processed without task-switching governed by executive systems. However, task switching between two high level tasks under executive control is probably the default way for a novice to perform a dual task.

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). Though the underlying processes responsible for a decrement in simple reaction time tasks may not be entirely clear, brain imaging has revealed the biological bases of limitations in these dual tasks; it has also revealed that some people may be able to overcome the limitation.

Training effects

Some studies have found that under certain circumstances, dual-tasking interference may be reduced or entirely eliminated. Dux et al. (2009) showed that training improved multitasking performance. (The delays in response associated with dual-tasking decreased from 400ms to 40 ms; moreover, the improvement in speed was not the result of trading away accuracy.) The brain imaging findings showed that the improvement after practice was associated with faster processing (activation occurring sooner) in the prefrontal cortex. As discussed above, after the training had occurred, the activation peak in this area occurred sooner.

Neural efficiency and improvement in higher-level dual-tasks. The amount of cognitive resources consumed to perform a task is a measure of the brain efficiency in task performance (Prat & Just, 2008). The consumption of brain resources can be measured in two related ways: the volume of tissue that becomes activated above some threshold, and the mean activation level of a volume (Just et al., 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 et al., 2003; Prat et al., 2007; Reichle et al., 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 readers 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 inferior frontal gyrus). 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 their 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 in simple-reaction dual-tasks. 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. After relatively modest

amounts of practice, a seminal study of dual-tasking showed that 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 videogame 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. 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 and Schneider, 2005; Haier et al., 1992). Dux et al. 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.

Videogame training and practice: improvement in selective attention and speed of processing

Action videogame 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.

One of the executive functions associated with the ability to maintain high levels of performance in multitasking environments such as action videogames is selective attention. 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 videogame players, compared to non-videogame players, have a marked advantage in visual selective attention (Green & Bavelier, 2003). In tasks where the player has to pick out a target that shows movement patterns different than 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 to 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 videogaming as a training regimen for dual-tasking improvements may help to reveal the brain bases of training effects in multitasking, multi-stimuli environments. The attractive and positive features of videogaming may provide a foundation for developing new instructional techniques. And that foundation will have a multitasking look to it.

The brain bases of improvement: what changes after multitask training

Bavelier et al. (2011) identified the neural bases of improved selective attention in action videogame 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, inferior frontal gyrus, cingulum, and intraparietal sulcus) in comparison to non-gamers. Because gamers recruit fewer cortical resources (showed greater neural efficiency) during game playing (without trading away accuracy), the authors argue that gamers were 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.

In 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 evidence of greater neural efficiency when operating simulated aviation tasks and playing first-person action games, respectively. Bavelier et al. (2011), as discussed above, 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, inferior frontal gyrus, cingulum, and intraparietal sulcus) in comparison to non-gamers. 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 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, videogame 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?

Few studies have addressed the issue of individual differences in dual-tasking. In a behavioral study of dual-tasking and the effect of task instructions, Schumacher et al. (2001) suggested that individual differences in participants' tendency to respond slowly or inaccurately determined the extent to which practice helped improve their dual-tasking performance. Dux et al. (2009) showed that improved performance due to training is associated with an increase in speed of processing in the prefrontal cortex. Bavelier et al. (2011) showed that gamers have a better early filter of irrelevant information and are able to free up cognitive resources that allows them to process more visual and spatial information simultaneously.

These 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 higher-span multitaskers in the network of brain areas associated with the task (Buchweitz et al., 2012).

As described above, 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 (inferior frontal gyrus, 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 lower-skilled individuals (e.g. Haier et al., 1988; 1992; Newman et al., 2003; Prat & Just, 2010).

In summary, three types of brain changes seem to underlie individual differences and training effects in multitasking. Training effects in simple choice reaction tasks were associated with *increased speed of processing by the prefrontal cortex* (Dux et al., 2009). In simple choice reaction time tasks, there seems to be a convergence of processes onto the prefrontal cortex that may be associated with active monitoring of the tasks or response queuing. Training produces a change (a speed-up) in the temporal organization of brain activation in this frontal area. A second type of change in multitasking was an *increase in synchronization (relative to the single task) between the task-related brain areas*. The successful participants showed a change in the temporal organization of their neural processing, a shift in the timing relation among nodes in the language network, 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 third brain factor associated with successful multitasking was *higher neural efficiency*, as reported by Jaeggi and colleagues. Together, these three types of brain changes indicate that multitasking requires faster, better synchronized, and less resource-intensive processing.

Multitasking in clinical populations. Lesion and clinical studies of multitasking have contributed to the understanding of the specific functions of areas of the executive network. Impairment of executive functioning is associated with degrading the ability to multitask. Executive functioning can be impaired by brain injury; for example, Dreher et al. (2008) showed that the extent of damage to the fronto-polar cortex predicted impairment in the management of multiple goals. Executive functioning is also impaired with age and by neurodegenerative diseases. Consequently, dual-tasking is also impaired with age. Craik and Bialystok (2006) studied a "cooking breakfast" task that required younger and older adults to cook five different foods at the same time, and set the breakfast table. Older adults showed age-related decrements in multitasking when compared to younger adults. Interestingly, the study also had groups of monolingual and bilingual older adults. The bilingual older adults performed better than their monolingual peers (Bialystok and colleagues have proposed that bilingualism is a protective factor for executive functions in older populations).

Lesion studies demonstrate the importance of the rostral prefrontal cortex (or frontal pole) for multitasking. As part of the general network of executive function, the characteristic processing style of this area is associated with executive processes (more specifically, the selection and maintenance of higher order goals with subsequent performance of other, sub-goals) (e.g. Badre & D'Esposito, 2009; Roca et al., 2011). A study investigated the effects of prefrontal cortex lesions by combining MRI-measured lesion maps (volume of damage to area BA10) and three neuropsychological tests. One of the tests, called the Hotel Task (Shallice & Burgess, 1991) evaluated deficits in strategic behavior in a multitasking situation. The patients with BA10 lesions were significantly outperformed by their controls in the multitasking test in both its measures of optimal time spent on each task and number of attempts at each task (Roca et al., 2011).

Neurogenerative diseases such as Alzheimer's and Parkinson's produce clear decrements in the performance of dual tasks. Early stages of Alzheimer's disease are associated with impairment in executive processes. Logie et al. (2004) showed a dual-task deficit in Alzheimer's disease patients when compared to their age-matched controls.

As previously described, the dual task performance of participants with autism was substantially poorer than that of the control group, despite the two groups having been equated in the performance on the component single tasks (Garcia-Villamizar & Della Sala, 2002). The autism group's deficit in multitasking may be attributable to a compromised cortical bandwidth.

Each of these clinical perspectives illustrates that many facets of brain systems have to function properly to enable effective multitasking, and it takes the malfunctioning of only one of those facets to disable multitasking. We ask a lot of our brains when we multitask, and our brains have to be in very good condition in order to comply.

Future directions: The neural circuitry of the multitasking generation

Cognitive and developmental 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 what most contemporary brains can now do, 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 will be interesting to determine the extent to which multitasking ability becomes a norm in an electronic age.

Although the benefits of multitasking are clear, learning and performance under conditions of distraction is a growing concern. Children seamlessly interact with computers, tablets, and peripherals at an increasingly younger age. The increasing interactivity and multiplicity of input streams can be seen in how television programs are also more and more interactive. It is reported that one third of young people use other media while watching TV; they are multitasking (Small & Vorgan, 2008). The label *viewer* itself may also need to change to refer to something more active.

One practical question is how education systems should evolve to keep up and perhaps guide the multitasking, digital native generation. More interactive learning tools seem to be in order. Also, it seems likely that brain imaging studies will help understand how to train both young and old brains to deal with an increasingly multistream world.

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