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Growing up multitasking: The costs and benefits for cognitive development

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A B S T R A C T

Current work, play, and learning environments require multitasking activities from children, adolescents and adults. Advances in web-enabled and multi-function devices have created a perceived need to stay "wired" to multiple media sources. The increased demand that these activities place on information processing resources has raised concerns about the quality of learning and performance under multitasking conditions. Young children, whose attention systems and executive functions are immature, are seen to be especially at risk. To evaluate these concerns the costs and benefits of "everyday" multitasking (e.g., driving, studying, multimedia learning) are examined in relation to the classic experimental literatures on divided attention in task-switching and dual-task performance. These literatures indicate that multitasking is almost always less efficient (time, accuracy) and can result in a more superficial learning than single-task performance. Alternatively, when the cognitive, perceptual, and response requirements of the tasks are controlled by the individual, when learning platforms are developmentally appropriate, and when practice is permitted, multitasking strategies can not only be successful but can result in enhanced visual and perceptual skills and knowledge acquisition. Future progress will come from advances in cognitive and computational modelling, from training attention and brain networks, and from the neuroergonomic evaluation of performance that will enable the design of work and learning environments that are optimized for multitasking.

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Introduction

In our fast-paced, electronic world multi-tasking has become the "new normal". The pressure to process more information, solve more problems, deliver more results, and to do so faster and in tandem with other activities is a growing expectation of children and adults alike. Examples abound as students take notes while listening to a lecture and keeping track of incoming instant messages; office workers talk on the phone while managing emails and reading documents; academics fine-tune a grant application while preparing for an imminent class; doctors listen to patients while checking their medical records on-line; drivers negotiate through traffic while texting or talking on cell phones; and children and teens do their homework as they listen to music and browse the web or keep an eye on social media. Even infants and toddlers interrupt their play with frequent glances to a background television program as elements of the content draw their attention. To some extent this is not new. Individuals have been multitasking for eons – as any parent, ER physician, air traffic controller, or short-order cook can confirm. As long as the activities are neither physically incompatible nor mentally demanding, multitasking can even seem effortless. What is new is the suddenness with which the multitasking phenomenon has accelerated over the past decade and come to pervade the way we work and play. Moreover, the widespread availability of high-speed information and communication technology (ICT) has fuelled the expectation that the human cognitive system can simultaneously process, integrate, organize, and respond to multiple sources of information efficiently and productively. This expectation is not limited to media multitasking but includes juggling any sequence of tasks including those in which media are combined with real life interactions (see Greenfield, 2009; Rosen, Carrier, & Cheever, 2010; Small & Vorgan, 2008).

The growing requirement for multitasking has generated debate in the popular media and has motivated researchers to examine the impact of multitasking on performance directly. One view is that multitasking enables (and is necessary for) the high-level efficiency and productivity that are essential for successful competition in contemporary work and learning environments. The gist of this argument is that multitasking promotes mental flexibility that can actually change the manner in which we learn and retain information, especially among children and youth whose neural plasticity is relatively high (Dye, Green, & Bavelier, 2009a, 2009b; Green & Bavelier, 2008; Lui & Wong, 2012; Maclin et al., 2011; Small, Moody, Siddarth, & Bookheimer, 2009; Small & Vorgan, 2008; Sparrow, Liu, & Wegner, 2011). Alternatively, the case has been made that multitasking diminishes performance, especially when task juggling produces interference, distraction, and ultimately errors, lost time, and mental stress (e.g., Abate, 2008; Bowman, Levine, Wait, & Gendron, 2010; Gupta, Bhoomika, & Srinivasan, 2009; Ophir, Nass, & Wagner, 2009; Rosen, 2008; Strayer & Drews, 2007). The roots of that argument go back to experimental literatures on divided attention, dual-task performance, and task switching dating at least to the 1930s – well before multitasking emerged as a cognitive and socially significant phenomenon. That literature indicated that the human information processing system has a limited capacity and that sharing resources among tasks usually comes at a cost for performance and productivity (e.g., Kahneman, 1973; Telford, 1931; Welford, 1952, 1967). This issue remains active and contentious, with much depending on the perceptual, cognitive and response requirements of the tasks involved (e.g., Levy, Pashler, & Boer, 2006; Monsell, 2003; Pashler, Johnston, & Ruthruff, 2001; Strayer, Drews, & Johnston, 2003) and also on a number of individual differences (Buchweitz, Keller, Meyler, & Just, 2012; Green & Bavelier, 2003; Ophir et al., 2009; Parasuraman, 2011; Watson & Strayer, 2010).

The goal of this review is to provide a synthesis of that literature with emphasis on the increasing expectation for multitasking among young children and youth. While the context for multitasking in toddlers and preschoolers is typically play, observation suggests that their use of individual media types (e.g., computers, hand-held games, TV, print) is increasing (Calvert, Rideout, Woolard, Barr, & Strouse, 2005; Lee, 2009), though estimates of multimedia usage are undocumented. Among older children, a recent report from the Kaiser Family Foundation (Rideout, Foehr, & Roberts, 2010) indicated that children and youth between 8 and 18 years of age spend about 8.5 hours per day using entertainment media – reading, watching television or video, listening to music, playing computer games, looking at websites, or messaging. During nearly two-thirds of that time they are also doing something else such as eating, doing chores, talking on the phone, completing homework, or using other media. Consistent with this trend, schools are increasingly incorporating multimedia and e-learning protocols into their curricula (e.g., see Clements & Sarama, 2009, 2011; De Jong & Bus, 2002, 2004; Greenfield, 2009; Mayo, 2009; Moreno, 2006; Nir-Gal & Klein, 2004; Sarama & Clements, 2004, 2009), perhaps without due consideration of the cognitive constraints on performance that multitasking imposes or the development limitations in attention, learning, and representational processes among the youngest users.

Overview

The review will begin with a consideration of multitasking in the context of the classic experimental literatures on divided attention in dual-task and task-switching performance. There is extensive information on adults' performance in those paradigms, though much less is available on children, for whom the prerequisite executive functions needed for success (e.g., working memory, inhibition, set shifting) are still immature. The findings from those literatures will then be compared with the literature on "everyday" multitasking that occurs in many current contexts (e.g., driving while using a cell phone; task interruption and resumption at work or school; monitoring social media during study; multimedia learning). The distinction between the "experimental" and "everyday" literatures is admittedly arbitrary and perhaps more a matter of the level of analysis than methodology, as many studies of everyday multitasking make use of experimental design and procedures. In this review, the experimental literature refers to those (typically laboratory based) studies of dual-task interference and task switching. Those tasks are formulaic and tightly controlled and as such can provide causal information on the component processes and variables that underlie them. They also provide a basis for testing explanatory theories and models of everyday multitasking. However, it has been argued that the tasks lack ecological validity in relation to the many scheduled and spontaneous tasks that individuals perform as part of their everyday lives. In contrast, studies of everyday multitasking (including experiments that aim to mimic real-life multitasking) include more naturalistic procedures and measures that provide insight into individuals' decision-making and time management strategies that are integral to effective multitasking in the real world. This review will include selective examples of everyday multitasking research with adults and children that illustrate these cognitive processes. Following this, several computational models of multitasking will be discussed. As multitasking behaviour is highly varied and complex, predicting the outcome of any set of tasks requires a rigorous analytic framework. Evidence from recent cognitive models of multitasking that have described and quantified the impact of interference from multitasking on performance in experimental and everyday contexts will be evaluated.

Next, the potential impact of multitasking on young children's developing attention will be considered. Although adolescents and young adults comprise the primary age demographic for whom everyday multitasking has become a way of life, school-aged children are increasingly showing patterns of play and learning that could be considered as "precursors" to multitasking. Likewise, infants, toddlers, and preschoolers are exposed to multitasking environments that provide concurrent sources of information that divide their attention during play and social interactions (e.g., background television). The important point here is that children's attention processes, especially the executive processes needed to resist distraction, sustain, and shift focus as appropriate, are not fully mature until late childhood or adolescence. Selective examples from the literature on distractibility and focused attention will illustrate how young children may or may not adapt to the multitasking environments that surround them.

Finally, a central issue for children and adults alike is the relationship between multitasking, learning, and the brain. A basic question is whether multitasking trains the brain to process information in new and different ways and if so, whether it results in better control and integration of incoming information or simply fosters a more breadth-based and superficial style of attention allocation to multiple inputs (see Carr, 2010). Recent research from cognitive neuroscience (e.g., the effect of action video gaming on attention allocation and learning) and the emergent field of *neuroergonomics,* will be examined for insights into the brain's capabilities and limitations during multitasking. In neuroergonomics, hemodynamic (e.g., fMRI) and electrophysiological (e.g., ERP) imaging methods are used to study the human brain in relation to performance at work (see special issue of *NeuroImage* "Neuroergonomics: The brain in action and at work", Parasuraman, Christiansen, & Grafton, 2012). The overarching theme of the review will be whether, and under what conditions multitasking can be a viable work and learning option, and how the variables that underlie the answer to these questions will change with age.

Multitasking and the deployment of attention

Fundamentally, the issue of multitasking in both experimental and everyday tasks is one of dividing and deploying attentional resources effectively. Implicit in this is the ability to flexibly select, focus and switch attention to the features of the environment that are currently most important or salient while resisting distraction from those that are less so (Posner & Peterson, 1990; Posner & Rothbart, 2007; Ruff & Rothbart, 2001). The basic questions that have fuelled research for decades concern the processes and mechanisms that drive the deployment of attention, how they develop across childhood, and the constraints under which they operate. Regarding multitasking, an important question is whether (or under what conditions) two or more tasks that require common perceptual, motor and cognitive resources can be performed either concurrently or sequentially. As William James (1890) noted prophetically in the *Principles of Psychology*, “the number of processes of conception that can go on simultaneously is not easily more than one unless the processes are very habitual” (p. 386). In that view, which has been shared by others (e.g., Kahneman, 1973; Navon & Gopher, 1979; Pashler, 1984, 1994), attention is a finite mental resource that fuels all cognitive activity. Depending on the requirements of the activity, the resource can be focused on a single task or feature or shared more broadly across several tasks or features. The results of many experimental studies indicate that when attention is divided or switched among two or more tasks, some degree of dual-task interference or switch cost is observed in slower reaction time, increased error, and extended task completion time (see Meyer & Kiernas, 1999; Monsell, 2003; Pashler & Johnston, 1989). As the experimental literatures on dual-task interference and task switching inform questions on the nature and effectiveness of everyday multitasking, they will be considered next.

Dual-task interference research

In the standard dual-task procedure two simple, speeded tasks are presented concurrently or with a very short delay between them and the individual responds to them simultaneously. For example, a participant must say aloud whether a tone is high, medium, or low in pitch (auditory-vocal task) and press a button to indicate whether a number is greater or less than 10 (visual-manual task). To assess interference, performance on each task done singly is compared with performance in the dual-task condition. Typically, responses to one or both tasks are delayed in the dual-task condition with the extent of interference depending on the demands for common perceptual, cognitive, or motor resources. The challenge has been to characterize the nature of those resources and the rules that determine how they are allocated during task performance. An early and still prominent metaphor for dual-task interference was that of an all-or-none central processing bottleneck (Broadbent, 1958; Newell & Simon, 1972; Pashler, 1994; Pashler & Johnston, 1989; Welford, 1952). In that view, the central processing (e.g., response selection; memory retrieval; decision making) that followed perceptual encoding and preceded response output, could take place for only one task at a time, so performance on a secondary task was delayed. The clearest evidence for such a bottleneck came from experiments in which participants performed two speeded tasks that required a response to two different stimuli presented at a brief *stimulus onset asynchrony* (SOA) that varied from 0 to 1500 ms. When the tasks were performed in the presented order, the basic finding was that as SOA decreased the reaction time (RT) to the second task increased, a delay termed the *psychological refractory period* (PRP) (Welford, 1952). This PRP effect was robust and seen in many tasks, including those with non-overlapping input and response modalities. The effect was neither eliminated nor markedly reduced by practice (see Levy & Pashler, 2001; Meyer & Kiernas, 1997b; Ruthruff, Johnston, Van Selst, Whitsell, & Remington, 2003; Van Selst, Ruthruff, & Johnson, 1999).

Although the evidence from the PRP paradigm was compelling, the idea of a single channel, central, response selection bottleneck did not go unchallenged. Others proposed that dual-task performance was mediated by a series of *adaptive executive control* (AEC) processes in which individuals have flexible control over the course of secondary-task processing (Anderson, 1982; Kieras, Meyer, Ballas, & Lauber, 2000; Meyer & Kiernas, 1997a, 1997b, 1999). Secondary task slowing at short SOAs was seen as a *strategic* rather than a *structural* property of the cognitive system. In the AEC model, successful dual-task performance depended on the conversion of declarative knowledge (i.e., verbal descriptions about task requirements) into procedural rules for performing the tasks, typically through practice. After the conversion, processes for performing two tasks simultaneously could be executed in parallel by an "executive cognitive processor" that managed peripheral perceptual-motor resources according to prevailing task priorities. Interference could result from incomplete conversion of declarative to procedural knowledge or from an "executive" decision that deferred some stages of one task while another task was under way. In that case, deferment acted like a bottleneck, though it could occur at different stages of processing (see also, Borst, Taatgen, & van Rjin, 2010). This was not trivial as it implied that the bottleneck was not immutable and that perfect time-sharing (i.e., multitasking) could be achieved under certain conditions. These were that the tasks (a) were given equal priority, (b) were to be performed quickly, (c) used different perceptual and motor processes, (d) put no constraints on temporal relations or serial order among responses, and (e) participants receive enough practice to compile procedural rules (Meyer & Kiernas, 1997b). Under those conditions, Schumacher et al. (2001) showed virtually perfect time-sharing between two choice reaction time tasks (audio-vocal and visual-motor) that had previously showed a PRP effect. Other efforts were made to find tasks or special conditions that could bypass the bottleneck (e.g., Logan & Gordon, 2001; Meyer & Kiernas, 1997b; Tombu & Jolicoeur, 2002, 2004). Although some appeared to do so, methodological artefacts and confounds made it unclear whether the bottleneck was actually bypassed or simply latent (Lien, Ruthruff, & Johnson, 2006; Pashler et al., 2001; Ruthruff, Pashler, & Klaassen, 2001; Tombu & Jolicoeur, 2004).

An alternative to bottleneck models are central capacity-sharing models in which processing of several tasks can occur in parallel by distributing limited mental resources differentially among them (e.g., Kahneman, 1973; Navon & Gopher, 1979; Navon & Miller, 2002; Tombu & Jolicoeur, 2003). In that case, less capacity is available for any individual task and performance can be diminished on any one of them. This is consistent with everyday experience in which one carries out several tasks simultaneously (e.g., having a conversation while driving and attending to the GPS) without apparent cost until one of them becomes effortful. At that point the resource has to be redistributed in a graded fashion (e.g., less effort is spent on conversation as traffic becomes heavy) to avoid error. Kemker, Stierwalt, LaPointe, and Heald (2009) showed such a graded sharing of resources experimentally in the differential effects of an auditory distractor (cell phone conversation) on a series of cognitive tasks depending on task complexity and the cognitive engagement required (also see Tombu & Joilcoeur, 2002). An issue in capacity-sharing models is whether capacity consists of a single domain-general resource (Broadbent, 1958; Kahneman, 1973) or multiple domain-specific resources (and how these should be defined and differentiated), or what actually constitutes a resource (see Just & Carpenter, 1992; Logan, 1979; Meyer & Kiernas, 1999; Navon & Gopher, 1979; Norman & Bobrow, 1975; Salvucci & Taatgen, 2008; Wickens, 1984, 2008).

In sum, there is no consensus on the nature of the limitation in human information processing during dual-task performance. Although all-or-none bottleneck models have been favoured, debate continues on whether the bottleneck is central or whether it could occur at other information-processing stages, whether it is structural (i.e., a part of the human cognitive/neural architecture) or strategic (e.g., an executive decision making process), on how it is implemented (i.e., serially or in a simultaneously, but weighted manner), and even if a bottleneck is an appropriate metaphor at all. What is evident is that when given two tasks to perform concurrently, the cognitive system is most often constrained and priority is given to one task at the expense of others. Further clarity may come with advances in cognitive neuroimaging (Dux et al., 2009; Dux, Ivanoff, Asplund, & Marois, 2006; Just et al., 2001; Marois & Ivanoff, 2005; Parasuraman, 2011; Tombu et al., 2011). For example, data from time-resolved fMRI indicated that the posterior lateral prefrontal cortex (pLPFC) met three criteria expected of the neural substrates of a central information processing bottleneck, it: was co-activated by tasks that shared neither sensory nor motor output modalities, was involved in response selection, and exhibited serial queuing of response selection activity under dual task conditions (Dux et al., 2006; Marois & Ivanoff, 2005). Other fMRI data indicated the pLPFC might be part of a larger group of structures in the frontal/prefrontal cortex that is believed to serve as a more general unified central attentional bottleneck for both perceptual encoding and response selection in dual task performance (Just et al., 2001; Tombu et al., 2011).

Task-switching research

In the standard experimental task-switching procedure participants try to complete two or more tasks by alternating between them rather than by working on them concurrently. Typical they are trained to respond (usually with a manual or verbal choice) on two simple tasks (e.g., word reading; colour and object naming; categorizing digits, letters, or words; responding to stimulus location) and then to perform each of them on discrete trials. On some trials the task changes (switch trials) and on others it does not (repeat trials). When performance on the two trial types is compared, the usual result is a robust "switch cost" seen in longer reaction times and increased error rates. This phenomenon was observed in a range of tasks and is affected by a number of procedural (e.g., task structure; bivalent stimuli in which the same stimulus is a cue to different tasks; response overlap or incompatibility) and cognitive (e.g., working memory; memory retrieval; cue encoding) variables (see Kiesel et al., 2010; Monsell, 2003; Vandierendonck, Liefooghe, & Verbruggen, 2010).

A major research question is to explain why the switch cost occurs and to identify the cognitive and neural mechanisms that underlie it. There have been two classes of explanation for the performance decrement. In one, the switch cost reflects the preparation time required for *task-set reconfiguration* (TSR) to occur. The reasoning is that as a person prepares to do a task a corresponding mental *task set* is adopted. This includes the organization of cognitive processes and mental representations of task-relevant stimuli, responses, and their corresponding stimulus–response (S-R) mappings that enable the person to carry out task requirements (Jersild, 1927; Rogers & Monsell, 1995). To switch tasks, an active, top-down process of TSR must take place. This can involve shifting attention between stimulus attributes or elements, or between conceptual criteria, retrieving goal states (what to do) and condition-action rules (how to do it) into working memory, or deleting them to enable a completely different task set. In contrast, on repeat trials TSR is not necessary and these processes are not invoked.

In the second class of explanations, the switch cost is said to occur because of interfering representations from the previously performed task. Allport, Styles, and Hsieh (1994) described *task-set inertia* as the persisting activation of previously used task-set features that interfere with responding to a stimulus that has been processed in the context of another task. Others have suggested that interference can disrupt performance when the stimulus-task associations that were acquired during a previous task become irrelevant and must be suppressed once the task changes. Interference can also occur in tasks where stimuli are associated with competing responses and competing task sets or when responses are bivalent. In all cases, the switch cost ostensibly reflects the time needed to overcome this interference (e.g., through trace decay; response inhibition). There is evidence that both sets of factors are involved in switch-cost effects, though the conditions that favour one or the other in any particular set of tasks are unresolved (see Kiesel et al., 2010; Koch et al., 2010; Vandierendonck et al., 2010).

Developmental research on dual-task interference and task switching

Until recently there was little developmental research on dual-task or task-switching performance in children. This was likely because the control of attention (selection, focus, shifting, resistance to distraction) and the cognitive processes (working memory, inhibition, task set flexibility) that the tasks require are immature in the early years (Best & Miller, 2010; Crone, Bunge, van der Molen, & Ridderinkhof, 2006; Garon, Bryson, & Smith, 2008; Ruff & Rothbart, 2001; Wiebe et al., 2011). When these tasks were used in developmental research it was often as a tool to assess age change in some aspect of cognitive capacity rather that performance on dual-task or task switching (i.e., multitasking) per se. Those studies indicated that many of the questions about the nature of, and the metaphors for the resources (e.g., space, efficiency, speed, energy, effort) that fuel cognitive capacity in adults' also dogged the developmental literature (e.g., Case, Kurland, & Goldberg, 1982; Kail & Salthouse, 1994; Howe & Rabinowitz, 1989, 1990).

Although the executive functions necessary for cognitive or executive control are late to mature, there is evidence that certain behaviours that emerge in late infancy and toddlerhood (e.g., regulation of eye movements, searching for hidden objects, sensitivity to spatial conflict, error detection, and emotion regulation) appeared to reflect developmental antecedents of more complex executive functioning (e.g., Posner, 2012; Rothbart, Sheese, Rueda, & Posner, 2011). An important goal of this research was to identify continuities in these processes across the nascent and mature components of executive or cognitive control (see Davidson, Amso, Anderson, & Diamond, 2006; Dibbets & Jolles, 2006; Sheesh, Rothbart, Posner, White, & Fraundorf, 2008). With this renewed interest, researchers developed a variety of child-friendly tasks that did not require the sophisticated verbal or reading skills found in the adult versions of dual-task and task-switching procedures. Several studies have examined children's (i.e., 7 years and older) performance and compared it to that of young and older adults (see Cepeda, Kramer, & Gonzales de Sather, 2001; Kray, Eber, & Karbach, 2008). The typical finding was a U-shaped function between age and performance with children and older adults showing a larger switch cost (i.e., longer reaction times, more errors) than young adults. All age groups benefitted from extra preparation time but the youngest children showed the poorest resistance to interference. Similarly, Dibbets and Jolles (2006) found that among 5- to 13-year-olds even the youngest children were able to switch on the Switch Task for Children, but that the switch cost was greatest among the youngest children and decreased with age. Other research with child-friendly versions of the switch tasks showed that in some circumstances (e.g., if the sorting dimensions are separated rather than integrated; if verbal self-instruction or metacognitive reminders to "think about" the current rule are given) even 3- to 5-year-olds could improve their switching performance (Deak, Ray, & Pick, 2004; Diamond, Carlson, & Beck, 2005; Kray et al., 2008).

A related literature on the development of dimension switching is consistent with these findings. When 3-year-olds were asked to sort sets of cards (e.g., the Dimensional Card Sorting Test) that varied on two dimensions (colour, shape) by shape (trucks or stars) they could do so correctly. However when asked to switch to sorting by colour (red or blue) they perseverated to the previously correct rule (response). They did this in spite of verbal instruction and trial-by-trial reminders, extensive practice, and being able to articulate the correct rule (Zelazo, Carter, Reznick, & Frye, 1997; Zelazo, Frye, & Rapus, 1996). When children are about 5-years-old, they begin to perform the dimensional switch correctly, but are still vulnerable to preservative error. Although the rule-switching task differs from the standard task-switching procedure (see Cepeda et al., 2001), both share a common switch cost in increased errors following instruction to change to a new dimension or task. Likewise, the presumed causes of the switch cost included the difficulty that children had in reconfiguring the task once the rule had changed, in reflecting on the two rules simultaneously and then acting on the correct one, and in inhibiting a previously correct response. The switch costs in both paradigms continued to decline across middle childhood, as these difficulties are slowly resolved. (Cepeda et al., 2001; Davidson et al., 2006; Dempster, 1992; Harnishfeger & Bjorklund, 1993; Kirkham, Cruess, & Diamond, 2003; Marcovitch, Boseovski, & Knapp, 2007; Zelazo et al., 1996). Collectively, these studies show that the ability to maintain and manipulate two different tasks in working memory is present at least in rudimentary form in young children. With age, they become better able to formulate and use more complex rule structures, including the higher-order if-then rules that are needed for successful task switching (Zelazo & Frye, 1998).

Interestingly, Bialystok and Martin (2004) reported that bilingual preschoolers were consistently more successful on the card-sort task than were unilingual children. They hypothesized that when bilingual children hear either language spoken, both are active in the brain and that they have learned to monitor the current context and inhibit the inappropriate representation, a skill that also generalized to other cognitive tasks that required rule-switching (also see Bialystok & Craik, 2010; Bialystok, Craik, & Luk, 2012; Craik, & Bialystok, 2006) and persists across the life span. Although this explanation is a likely one for language users, several recent studies have reported a cognitive advantage for preverbal bilingual over monolingual exposure infants on several tasks that involved rudimentary rule switching, inhibition, and transfer of learning. For example, Kovacs and Mehler (2009b) reported that 12-month-olds who were exposed to two languages at home were more flexible in learning which of two particular speech structures (e.g., ABA, AAB) signalled the location of a toy across a series of switch trials, than were monolingual infants. In a second study, they reported that 7-month-olds raised in bilingual homes were more adept at using either verbal or visual cues to rapidly switch their gaze to a new location (i.e., inhibit their looks to the first location) in anticipation of the appearance of a toy, than were unilingual infants (Kovacs & Mehler, 2009a). Sebastian-Galles, Albareda-Castellot, Weikum, and Werker (2012) showed that compared with monolingual infants (Spanish or Catalan), bilingual 8-month-olds (both languages) were better able to detect and remember the perceptual cues that distinguished one unfamiliar language from another (French and English). Finally, Brito and Barr (2012) found that compared with monolinguals, bilingual 18-month-olds showed greater cognitive flexibility in generalizing cues associated with one exemplar in a deferred imitation task to a novel exemplar, an advantage that was evident as early as 6-months of age (Barr & Brito, 2014). Collectively, the findings from these studies indicate that bilingual exposure might have acted in a number of ways to facilitate the development of the control and selection abilities that infants needed to monitor and extract structural regularities from two different language streams. Further, that in the process of keeping their two native languages straight, bilingual infants might have acquired a transferable skill set (e.g., enhanced perceptual attentiveness, rule switching) that conferred them with the cognitive advantages they have been seen in several linguistic and non-linguistic domains.

Summary of dual-task and task-switching research

As with the dual-task paradigm, the task-switching procedure has been useful because of its simplicity, the potential for many variations, and the good experimental control it permits. For those same reasons, it has limited direct application to real-world tasks. For example, little attention has been paid to user-defined tasks and goals, voluntary task switching, or task interruption. That being said, the experimental procedures have enabled a micro-examination of some of the functional aspects of cognitive control (e.g., the processes that enable flexible switching; factors responsible for the switch cost; task-set reconfiguration processes; resistance to interference; rule representation) that are also relevant to everyday multitasking. Although the dual-task and task-switching literatures have evolved separately and with little cross talk, they can be considered as lying on a temporal continuum. The time between task switches could range from sub-second intervals for concurrent (or dual) task performance to several minutes or hours for sequential (task switching) performance. Although the boundary between the two extremes is not definitive (e.g., complex tasks can involve concurrent and sequential components), the approach provides the basis for a unified view of everyday multitasking performance (e.g., Adler & Benbunan-Fich, 2012; Salvucci & Taatgen, 2011). Finally, the lesson from these experimental literatures is that human information processing is indeed a limited capacity system and that engaging in either of these task strategies will come at a cost that does not bode well for the effectiveness of everyday multitasking. Limitations are likely to be especially marked in children, whose executive functions and control processes are immature. This reality contrasts with the belief among many multitaskers, that their performance is not hindered compared with single-task performance and is sometimes even better (Ophir et al., 2009; Rideout et al., 2010; Strayer et al., 2003; Watson & Strayer, 2010).

Everyday multitasking

The reality of everyday multitasking has generated a large and diverse literature on its effectiveness and on the cognitive resources and processes that are required for success. Although there is no consensus, one general concern based on the dual-task and task-switching literatures is that multitasking is detrimental to the speed and accuracy of performance on a wide range of tasks. Others worry that multitasking (especially media multitasking) fosters a strategy of paying “continuous partial attention” (Stone, 1998; cited in Rosen, 2008) to a variety of information sources without focusing on any one of them. Alternatively, the case has been made that in the real world participants have greater flexibility in task prioritization and multitasking can result in adaptive strategies for improved efficiency by altering the way that we process information and enabling “more things to get done” and to “do more with less” in a day. There is also evidence that task switching can foster creativity when it provides a respite from complex tasks and an opportunity for consolidation and insight (Madjar & Shalley, 2008). An intermediate position is that multitasking can be more effective than single tasking up to a point after which there is a performance decrement in accuracy and productivity (e.g., Adler & Benbunan-Fich, 2012; David, Xu, Srivastava, & Kim, 2013). Some of this uncertainty will likely be resolved by innovations in neuroergonomics and computational modelling in which accurate and independent assessment of resource competition, cognitive workload, and underlying neural activation in everyday multitasking is becoming possible (Just, Carpenter, & Miyake, 2003; Kramer & Parasuraman, 2007; Parasuraman, 2011; Schultheis & Jamieson, 2004). There is also evidence that attention training and brain state training can strengthen self-regulation and enhance both behaviour and the brain networks that underlie attention (Tang & Posner, 2014). In the meantime, the challenge for research is to identify common core processes that characterize everyday multitasking across the diversity of tasks, contexts, and individuals that comprise it. It is also clear that multitasking itself must be clearly specified as the different multitasking strategies that vary in the extent of task overlap (sequential, parallel, interleaved) will predictably affect performance outcome (Adler & Benbunan-Fich, 2012; Judd, 2013; Salvucci & Taatgen, 2011). For developmentalists the added challenge is to assess the constraints of children's immature attention and cognition on the functioning of those common processes in the everyday world.

Interruption, suspension, switching, and resumption of everyday tasks

Much of everyday multitasking involves working towards several goals within a time frame and distributing attentional focus and cognitive effort among them in a discretionary manner. A student writing a term paper might be interrupted by a ping from incoming social media, a phone call requesting information, or a signal that an incomplete project is due tomorrow. Company employees are given an increasing variety of responsibilities and tasks to complete in a day and are expected to use an assortment of digital and electronic technologies to switch among them. Gonzales and Mark (2004) reported that office managers, software developers, and analysts in a financial institution spent about 3 minutes on a given task (e.g., phoning, emailing, using a computer or calculator, paperwork, reading books, talking to co-workers, formal or informal meetings, personal time) before switching to another task. A time use study that compared emergency room and primary care physicians indicated that the ER physicians experienced significantly more interruption and managed more patients concurrently than did primary care physicians (Chisholm, Dornfield, Nelson, & Cordell, 2001). Although the demands of these (and other) work environments differ significantly, task interruptions, suspensions, switches and resumptions have come to characterize the typical working day in ways that will affect performance.

As with the classical dual-task and task-switching paradigms, everyday multitasking is subject to potential interference that arises from competition among the perceptual, motor and cognitive resources that the tasks require. As everyday task switching runs a more variable time course across more complex activities, there are additional sources of interference. One such source is the *problem state* that each task requires. A problem state (akin to a task set) is a cognitive resource that stores and keeps track of the task-related information required during the execution, suspension, and resumption of the tasks (Borst et al., 2010). As an individual can only keep one problem state active in working memory, when a problem state has to be maintained (i.e., rehearsed) or stored and then retrieved (i.e., reconstructed) during task switching, they consume cognitive resources and become a source of interference. By implication, declarative memory itself can be a source of interference during multitasking when its processes are required by the tasks and subtasks for information storage and retrieval. Once interference from all sources reaches a critical point, a bottleneck will occur and work on one of the tasks will be suspended for later resumption (see Altmann & Gray, 2008; Anderson, Albert, & Fincham, 2005; Borst et al., 2010).

However, research shows that certain task, context, and individual factors interact with the operation of the problem state. For example, a task interruption and suspension can be initiated externally (e.g., a phone call) or internally (e.g., decision to take a break). Though the latter may seem less disruptive, Adler & Benbunan-Fich (2013) reported that self-interruptions were associated with more task switching and lower accuracy on a series of tasks when the individual experienced negative feelings (e.g., frustration, obstruction, exhaustion) about task outcome. Positive feelings about a task (stimulation, exploration, reorganization) resulted in fewer self-interruptions, less task switching and better performance. So the impact of both external and internal interruptions will depend on the timing, duration, and complexity of the ongoing task activity and on the individual's affect towards the task. Moreover, interruptions that occur between subtask components are less disruptive than those that occur within a subtask. Interruptions within a subtask necessitate problem state maintenance if the duration of the suspension is brief. If the suspension is extended, or if the task is complex, or continues to evolve during the suspension, the problem state will have to be reconstructed (Iqbal & Bayley, 2005; Monk, Boehm-Davis, & Trafton, 2004). These processes consume cognitive resources and contribute to the resumption lag that is commonly experienced as the time needed to recover or "get back into" a primary task that has been suspended (see Altmann & Trafton, 2002; Dabbish, Mark, & Gonzalez, 2011; Monk, Trafton, & Boehm-Davis, 2008; Salvucci & Taatgen, 2011; Tremblay, Vachon, Lafond, & Kramer, 2012). When students experienced interruptions that prevented rehearsal of the primary task during task suspension they performed more poorly than those who were able to rehearse the primary task goals (Cades, Trafton, Boehm-Davis, & Monk, 2007). Interruptions during periods of high cognitive engagement with the task will also be more disruptive to task resumption than interruptions during periods of lower cognitive engagement. In fact, when task suspension is under the individuals' control they are more likely to defer during a period of high (e.g., difficult task) than low (e.g., easy task) cognitive engagement (Salvucci & Bogunovich, 2010). Consistent with this, students who read and responded immediately to text messages during a lecture performed more poorly on study material than did those who deferred responding until a more appropriate break point (Rosen, Lim, Carrier, & Cheever, 2011). The individual's reason for electing task suspension is also important. These might include time constraints, interest or motivation, an impasse in the primary task, subtask completion, or some external cue, but are generally timed to facilitate task performance after resumption (Jin & Dabbish, 2009). For example, Payne, Duggan, and Neth (2007) gave college students word search games (e.g., Scrabble) that were time-limited, varied in difficulty, and could be worked on in any order. Participants made deliberate decisions about when to switch between tasks based on "cognitive foraging" heuristics such as reward optimization, likelihood of success, or subtask completion.

Individual differences in effective multitasking

The diversity of everyday multitasking situations and the complexity of the interactions among the individual, the task requirements and the contextual factors that can affect performance make predicting multitasking outcomes difficult. To address this, researchers have tried to move beyond assessing particular occupations or work settings and to looking for individual differences that might characterize successful or unsuccessful multitaskers. Such a general, special "time-sharing ability" or talent would enable researchers, educators, and employers to identify those who would likely be successful across a variety of work settings in which dual-task or task-switching performance is required. For example, Hambrick, Oswald, Darowski, Rench, and Brou (2010) examined success on a simulated work task program that included requirements for multitasking that are common across many situations (i.e., time-constrained, fast-paced tasks with different priorities, goals, and payoffs). They found that working memory capacity was a key predictor of multitasking success as was participants' choices of the most effective strategies for task performance. In contrast, the contribution of processing speed to success was weak. Although intelligence is the best single predictor of job performance in many domains (Schmidt & Hunter, 1998), Colom, Martinez-Molina, Shih, and Santacreu (2010) reported that both the processing and storage components of working memory were better predictors of performance on tests of air traffic control skills than was intelligence. Logie, Trawley, and Law (2011) also identified working memory as critical to successful multitasking. Young adults were tested with the Edinburgh Virtual Errands Test (EVET), a series of "naturalistic" errands that imposed significant memory and planning demands. The results showed that measures of retrospective memory, visuo-spatial working memory, and online planning collectively predicted the EVET multitasking score, but independent measures of verbal working memory and prospective memory did not (but see Burgess, Veitch, Coltello, & Shallice, 2000; Buchweitz et al., 2012; Colom et al., 2010). Finally, Werner et al. (2011) found that working memory capacity and good spatial skill predicted college students' efficiency in resuming an interrupted task (also see Morgan et al., 2013).

Collectively, these findings are not surprising as working memory is a key component of executive functioning and is critical to making switches between tasks, maintaining a focus of attention during potential distraction, and pursuing goals that underlie the ability to engage in multitasking (Morales, Calvo, & Bialystok, 2013; Posner, 2012).

Working memory alone is not a sufficient condition to support effective multitasking. Strayer and Watson (2012) controlled for working memory in a group of "supertaskers" who could complete two tasks (e.g., driving and cell phone use) as effectively as each task singly. These rare individuals comprised 2.5% of a larger group of participants. Subsequent neuroimaging studies indicated that supertaskers' brains showed less activity at the more difficult levels of a multitasking test, whereas control participants showed the more typical pattern of recruiting more neural resources with task difficulty. The supertaskers differed most notably from controls in the three frontal brain areas (frontopolar prefrontal cortex, dorsolateral prefrontal cortex, anterior cingulate cortex) that earlier research had identified as important for multitasking. There is also evidence that supertaskers may have unique genetic features that could be related to more efficient information processing in these individuals. Strayer and Watson have reported preliminary evidence that supertaskers might possess a variant of the COMT gene that could alter the efficiency of dopamine signalling in the regions of the brain that support multitasking (Strayer & Watson, 2012), though further research is necessary to confirm this.

Researchers have also examined "polychronicity" in relation to multitasking success. Operationally, polychronicity is the extent to which individuals prefer to be engaged in two or more tasks or activities at a time and who also believe that this is the best way to get things done (Conte & Gintoft, 2005; Conte & Jacobs, 2003; Poposki & Oswald, 2012). Characteristics that have been associated with polychronicity include, extroversion, agreeableness, general mental ability, openness, stress tolerance, achievement striving, and Type A personality. Kantrowitz, Grelle, Beaty, and Wolf (2012) examined polychronicity and work performance on a range of managerial and non-managerial occupations that required multitasking and confirmed that the characteristic predicted successful performance across the range of tasks and occupations, though there is some evidence that it may be most critical when the person–work requirement for multitasking fit was optimal (Hecht & Allen, 2005; Sanderson, Bruk_lee, Viswesvaran, Gutiere, & Kantrowitz, 2013). Others have found that polychronicity is best characterized as a mediating factor in multitasking success when other personality characteristics such as impulsiveness, trait self control, and sensation seeking are considered (Grawitch & Barber, 2013; Konig, Oberacher, & Kleinmann, 2010; Sanbomnatsu, Strayer, Medieros-Ward, & Watson, 2013; Strayer & Watson, 2012).

Taking a different approach to individual differences, Ophir et al. (2009) gave college students, who had self-identified as light or heavy media multitaskers in their daily lives, several cognitive tests designed to measure aspects of distractibility. The authors hypothesized that heavy multimedia users might have (or have acquired) a breadth-based style of cognitive control that would enable them to divide their attention among different sources of information more readily than light users. For example, high multitaskers might have a more effective "skimming" strategy in which they could process the highlights of information while ignoring peripheral or incidental details (Duggan & Payne, 2009). Contrary to expectations, heavy compared with light multitaskers were less well able to filter out distractions and irrelevant information from working memory and performed more poorly on a standard measure of task switching (but see Minear, Brasher, McCurdy, Lewis, & Youbggren, 2013). Consistent with this, Sanbonmatsu et al. (2013) asked college students to rate their frequency of multitasking and their perceived ability to do so effectively and then gave them a multitasking test. They also rated the participants on impulsiveness and sensation seeking. Those high in real world multitasking had lower working memory, were higher on impulsiveness and sensation seeking, and were poorer on the multitasking test. Yet they tended to rate their own ability as significantly higher than average. The authors concluded that overconfidence and impulsiveness rather than skill appeared to drive their extensive real world multitasking choices. Although individual differences are clearly an important consideration in predicting successful multitasking, much more research is needed to identify, explain, and integrate these complex person, task, and contextual variables (Buchweitz et al., 2012; Engle, 2002; Ishizaka, Marshall, & Conte, 2001; Watson & Strayer, 2010).

Research on everyday multitasking: selective examples

Although questions about the appropriate time and place for multitasking as an effective strategy for work or study cannot be answered definitively, there are several domains in which the results of substantial research have provided valuable insights. Several of these will be reviewed to illustrate what is known, what is still to be known, and where to direct future research. The domains to be reviewed include (a) driving and driver distraction, (b) learning and academic performance, and (c) learning with new technologies. These were selected for the importance of their cognitive and social consequences and for their potential to resolve some complex questions about everyday multitasking.

Driving and driver distraction

Driving is a complex task that involves a number of interleaved subtasks that are performed concurrently or in alternation. Although the driving task does not have developmental implications per se, it provides a well-researched illustration of the task concurrency, interruption, suspension, switching and resumption that occurs in everyday multitasking. Driving subtasks include perceptual-motor activities such as steering control, changing lanes, manoeuvring through traffic, braking and acceleration as well as ongoing cognitive tasks such as planning, decision making, or maintaining conversation with a passenger. When these subtasks are combined with interactive in-vehicle devices such as phones, navigation aids, or portable music devices the driving task becomes even more complex and the potential for distraction higher (Haigley, Taylor, & Westerman, 2000; Horrey, Wickens, & Consalus, 2006). Indeed, *National Highway Traffic Safety Administration* (NHTSA, 2011) survey data indicated that in 2009 just under half a million people were killed or injured in car accidents that involved a documented driver distraction and about half of those were cell-phone related.

There is a growing literature on the factors and combinations of factors that cause secondary task interference during driving (see Horrey & Wickens, 2006; Salvucci & Taatgen, 2011). In one study, Levy et al. (2006) had college students perform two tasks simultaneously during a realistic driving simulation using the PRP procedure. In a choice task they responded either manually or vocally to the number of times (one or two) a stimulus (visual or auditory) occurred. In a braking task, they depressed a foot pedal when a lead car also braked. The results showed that the braking task RTs increased significantly during the concurrent choice task (especially at short SOAs), showing the typical PRP effect. When participants were instructed to ignore the choice task and to give priority to the braking task, most continued to show longer braking RTs (Levy & Pashler, 2008). Clearly, even a simple and well-practiced task such as vehicle braking is subject to dual-task interference.

However, not all distractions are equally disruptive to performance with much depending on the demands of the secondary task and the extent to which it engages the attention of the driver (Haigley et al., 2000; Horrey et al., 2006). Research shows that the most significant distractions arise from tasks that interfere with the visual and/or motor demands of driving. For example, driving while dialling a cell phone or text-messaging have a consistently negative impact on performance (e.g., reaction times, steering control, gap estimation, braking) (Alm & Nilsson, 1994; Brookhuis, De Vries, & De Waard, 1991; Drews, Pasupathi, & Strayer, 2008; Drews, Yazdani, Godfrey, Cooper, & Strayer, 2009; Horrey & Wickens, 2006; Reed & Green, 1999; Salvucci & Macuga, 2002) and create a potential level of distraction equivalent to intoxication with a blood-alcohol level of .08 (Strayer, Drews, & Crouch, 2006). Other studies have reported interference from driver interaction with in-vehicle devices such as radios or MP3 players (Haigley et al., 2000; Horrey et al., 2006; Salvucci, Markley, Zuber, & Brumby, 2007; Sodhi, Reimer, & Llamazares, 2002), email systems (Lee, Caven, Haake, & Brown, 2001), and navigation devices (Lee, Forlizzi, & Hudson, 2008). However, minimizing the visual and motor demands of an in-vehicle task does not eliminate interference effects from driving. Certain cognitive tasks (e.g., mental arithmetic, working memory, verbal rehearsal, conversation) can also impede driver performance when there is competition for the same procedural resource (Levy et al., 2006). For example, Just, Keller, and Cynkar (2008) reported that participants who listened to sentences that required a true or false judgement as they navigated a driving simulator, showed poorer driving compared with those who drove undisturbed. Moreover, fMRI data showed that parietal lobe activation that was associated with spatial processing in the undisturbed driving condition decreased by 37% during the sentence task.

Strayer et al. (2003) reviewed studies in which distraction from cell phone conversation was compared with other auditory–verbal activities that are commonly performed during driving. They reported that listening to a radio or to books on tape did not interfere with drivers' detection of, and reaction time to simulated traffic signals, whereas both hand-held and hands-free cell phone conversations did impair performance (Strayer & Johnston, 2001). The latter finding is important as it is widely believed that hands-free cell phone use is less disruptive to driving than is a hand-held device (also see Horrey & Wickens, 2006). Consistent with this, McCarley et al. (2004) found that the detection of changes in real-world traffic scenes was impaired when participants conversed on a hands-free phone although no impairment was observed when they passively listened to pre-recorded conversations. Strayer and Johnston (2001) also found that a simple shadowing task did not interfere with driving simulation performance but as the shadowing task became more complex, impairment was more evident. Collectively, these findings suggest that it is neither the listening to, nor producing vocal outputs per se that interferes with driving but the degree of cognitive engagement in the conversation.

In sum, driving is an everyday multitasking activity that is highly vulnerable to interference from many sources. Even when component driving skills are well practiced, they continue to draw on common processing resources. If in addition, the driver is engaged in other cognitive (e.g., thinking about work or personal matters) and in-vehicle activities (e.g., cell phone use, conversing), the driving task becomes more complex. That being said, Watson and Strayer (2010) identified a small number of young adult "supertaskers" who were able to drive in a simulator as they performed a complex task of auditory working memory without showing decrement in either task. Although education and legislation may curb the use of certain in-vehicle activities (e.g., text messaging) it is unlikely that the driving environment will become simpler as new in-vehicle devices (computers; video players; navigation aids) become available. However, it is important to note that most findings have been obtained in driving simulators rather than in real-world driving conditions. A limitation of this is that it does not account for the in situ flexibility of real-world driving or the metacognitive processes whereby drivers plan and react to situations that occur unexpectedly as they navigate the highway environment. Haigley et al. (2000) reported that some participants engaged in a process of "risk compensation" by reducing their speed (and their cognitive load) as they talked on a cell phone. Also, drivers and passengers will modulate their conversation based on awareness of current driving conditions and the real-time demands of driving (Drews et al., 2008). Finally, statistically significant interference effects found in simulated conditions should be interpreted in the broader natural driving context if they are to be meaningful (see Salvucci & Taatgen, 2011).

Learning and academic performance

Teens and young adults are among the heaviest media multitaskers in school and other learning environments (Carrier, Cheever, Rosen, Benitez, & Chang, 2009; Foehr, 2006; Jeong & Fishbein, 2007; Rideout et al., 2010; Rosen, Carrier, & Cheever, 2013). Indeed, many students report that they can listen to music, watch TV, scan e-readers, check e-mail, and communicate with friends through social media while studying or doing homework without any loss in performance. Some say that multitasking helps them to concentrate (Roberts & Foehr, 2008). Moreno et al. (2012) sent six text messages at random times during the day to college students whose replies indicated that more than half of the time that they were using the Internet they were also multitasking, most often with social media. This is perhaps surprising given that several decades of research indicates that the human information processing system is ill equipped to attend to multiple sources of input at once, to perform two tasks simultaneously, or to engage in frequent task switching without incurring a response cost. However, it may be that students are simply unaware of degraded performance until the tasks become physically incompatible or mentally demanding or until a time constraint is imposed (Carr, 2010; Pool, Koolstra, & van der Voort, 2003; Pool, van der Voort, Beentjes, & Koolstra, 2000). Consistent with this, Brasel and Gips (2011) found that students were poor judges of their media multitasking behaviour and significantly underestimated the duration of their looks and the number of times they switched their gaze back and forth from television to the computer. The broader significance of this is that the brevity of students' looks to either media (M = 1.7 s for television; 5.3 s for computer) identified them primarily as "monitoring" and "orienting" looks in which only superficial information processing occurs (Hawkins, Pingree, Bruce, & Tapper, 1997).

There is a substantial though diverse literature on the real-world consequences of multitasking for educational outcomes (e.g., Fox, Rosen, & Crawford, 2009; Fried, 2008; Junco & Cotten, 2011, Junco & Cotten, 2012; Kirschner & Karpinski, 2010; Lee, Lin, & Robertson, 2012; Mayer & Moreno, 2003; Rosen et al., 2011; Wood et al., 2012). However, the studies reflect an assortment of tasks, conditions, methods, and measures that make the data difficult to interpret across studies and meaningful conclusions elusive. At a general level, it seem clear that although digital technologies typically distract learners and impair performance on many tasks, there are exceptions. As with any activity that involves task interruption and resumption, the type and difficulty of the tasks, the timing and duration of the interruptions, students' engagement with the primary task, and certain individual differences are important considerations.

A brief sampling of this literature indicates that students who: (1) were frequent multitaskers also paid less attention to lectures, admitted poorer understanding of the course material, and received lower grades than did infrequent multitaskers (Fried, 2008), (2) used Facebook and texting while studying had a poorer overall college GPA than those who did not, although the time spent e-mailing, web browsing, phoning, and instant messaging was not related to college GPA (Junco & Cotten, 2011, 2012; Wood et al., 2012), (3) reported spending time instant messaging during study also reported higher distractibility for academic tasks, while the time spent reading was negatively related to distractibility (Levine, Waite, & Bowman, 2007), (4) replied to instant messages as they read an academic passage online took longer to complete the reading but showed equal comprehension of the passage as students who did not message during study (Bowman et al., 2010), (5) received eight text message interruptions during a 30 min lecture performed more poorly on a test of the lecture material than those who received four or no texts (Rosen et al., 2011), (6) were given a reading comprehension assignment with a to-be-tested video playing in the background did more poorly on the test that did students who worked in silence or with the same, but not-to be-tested video in the background (Lee et al., 2012; Lin, Lee, & Robertson, 2011), (7) had in a cell phone conversation while doing cognitive tests were able to perform as well as no-phone controls on simple tasks but not on more difficult tasks (Kemker et al., 2009), (8) were only able to maintain attention to important to-be-tested study material for a brief time (less than 6 minutes) during a 15 minute observation before switching to check out other available media (Rosen et al., 2013).

Although cognitive engagement and task complexity per se were not evaluated directly in most of the studies, a plausible conclusion is that media multitasking is detrimental to academic performance when it leads to cognitive overload, but in conditions of lesser load it need not diminish performance, especially when there is no time limit on task completion (Mayer & Moreno, 2003). In addition, recent research has indicated that beyond the effects of increased cognitive load, students also reported an emotional need to interrupt their primary activities by checking in regularly with social media and that they felt highly anxious when prevented from doing so (Rosen et al., 2013; Wang & Tchernev, 2012). As multitasking with diverse media appears to be here to stay, Rosen et al. (2013) proposed that rather than trying to prohibit such use in academic settings, that educators might use the findings of recent research to develop adaptive strategies that optimize student learning within the multitasking milieu.

Learning with new technologies

Today's schools are populated with children and teens ("digital natives") who do not know a world without cable television, Internet, smart phones, action video games, video recorders, email, texting, and social media. They seem to work and play comfortably amid multiple concurrent media sources. Though many of their activities involve self-directed entertainment and are without time constraints, these children are effectively multitasking as their attention is divided among diverse sources of input and responses that compete for common resources are often required. Not surprisingly, schools have come under pressure to take advantage of students' facility with ICT and electronic media by incorporating them into formal learning environments (Greenfield, 2009; Karsenti & Collin, 2012). This typically involves the presentation of multiple sources of information on a single monitor with several open windows, or via interactive white board technology (e.g., SmartBoard) with especially designed educational software, or through a video games format with imbedded educational content (e.g., linear algebra, ecology, immunology, geography). Although these "multitasking" platforms are designed to be interactive, motivating, and self-paced, they also require students to divide their attentional resources across the windows and to switch among tasks or subtask within a window. This can place the user (especially the young user) at risk for cognitive overload rather than the enhanced learning outcomes and greater self-efficacy that are the goals of multimedia learning (see Mayer, 2005; Mayo, 2009). Although the effectiveness of these new tools has been reviewed, many evaluations have been limited to whether or not children and teachers are satisfied with these technologies. There are few well-controlled studies on their effectiveness as learning platforms and the results that have been reported are mixed, in part because "technologies" are not equal in their design or in the cognitive resources required for their use (see Bavelier, Green, & Dye, 2010; Owen et al., 2010; Subrahmanyam & Greenfield, 2008).

One common multimedia approach has been to add interesting information or other "bells and whistles" (e.g. animations) to on-screen presentations that may or may not be related of the core material but that compel the viewers' attention and increase arousal, motivation, and engagement. Mayer, Heiser, and Lonn (2001) had college students view an animation and listen to concurrent narration explaining a scientific concept. Students who received redundant on-screen text that summarized or duplicated the narration performed worse on tests of the concept than those who heard the narration only. When interesting but irrelevant details were added to the narration performance also deteriorated, negating the hypothesis that arousal alone can facilitate performance. Similar effects were observed in a study in which the visually complex CNN Headline News format was used to assess students' recall of news stories (Bergen, Grimes, & Potter, 2005). This format has a news anchor reading the stories with additional weather forecast icons, sports scores, stock prices, and text presentations of other news stories as "crawls" at the bottom of the screen. The students recalled less of the primary news stories in the complex format than those who viewed the broadcast without the additional material (see Mayer & Moreno, 1998, 2003). Not surprisingly, "more is less" among younger children as well. Acha (2009) found that 8- to 9-year-old Spanish-speakers who read an English story presented on a computer learned new vocabulary more readily when words were translated and presented as text compared with pictures or both text and pictures. Likewise, Fisher, Godwin, and Seltman (2014) reported that kindergarten children who took science lessons in a highly decorated classroom were more distracted by the visual environment, spent more time off task, and had smaller learning gains than did children who took the lessons in an undecorated room. It appears that in all of these studies, rather than enhancing learning, the extra material (even when relevant) seemed to distract students from the main message, added to their cognitive load, and interfered with learning. Consistent with this are several large-scale studies in which computer software programs designed to improve language and literacy skills in primary school children were found to be no more effective than conventional methods (Dynarski et al., 2007; Rouse & Krueger, 2004).

In contrast to the literature that showed performance decrements in multimedia learning, other evidence shows enhanced performance from these formats. Tuzun, Yilmaz-Soylu, Karakus, Inal, and Kizilkaya (2008) showed that compared with learning in the traditional school environment, primary school children made significant academic and motivational gains after participating in a computer-based geography curriculum presented in a game format. Karsenti and Collin (2012) reported survey, interview, and observational data that students from 7 to 17 years old who were provided with laptops in school improved their academic performance, showed better attention, motivation, independent learning, interaction with teachers and peers, and improved ICT literacy skills. Programs in which science and mathematics information was provided in videogame format to middle school, high school and college students showed a significant advantage over the same information presented by the traditional lecture method (see Anderson & Barnett, 2013; Mayo, 2009; Owen et al., 2010). Other reported benefits to children given age-appropriate experience with computer learning include increased attention span (Vernadakis, Avgerinos, Tsitskari, & Zachopoulou, 2005), metacognitive skills, math skills, and concept knowledge (Clements, 2001), and nonverbal skills, memory, manual dexterity, verbal skills, and problem-solving abilities (Nir-Gal & Klein, 2004). In spite of the lack of good quantitative research on the quality of children's learning, there seems to be a consensus that ICT potentially has much to offer when the software is carefully designed and implemented in a developmentally appropriate framework and delivered in a supportive environment by motivated and informed instructors (Clements & Sarama, 2011; Mayer & Moreno, 2003; Mayo, 2009; Segers, Verhoeven, & Hulstijn-Hendrikse, 2008; Sheery, 2013).

A significant trend in the use of ICT in learning environments is the decreasing age of the demographic that is participating. According to a Kaiser Family Foundation survey, by the time children are 4–6 years old, 70% have used a computer (Rideout & Hamel, 2006). However, many younger children are developmentally ready to use computers and show confidence in using software packages designed for them (Ellis & Blashki, 2004; McKenney & Voogt, 2010; Plowman, Stevenson, Stephen, & McPake, 2012). Calvert et al. (2005) reported that preschoolers who were computer users began at about 2.7 years by depressing keys to produce interesting effects and by 3.5 years could use a keyboard and mouse. Children could also follow pictorial directions and use visual cues to understand and think about their activities (Clements, 2001). Lee (2009) found that preschoolers were able to use a computer program that highlighted basic science skills of observation, prediction, classification, sorting, and sequencing in a child-friendly game format but were more likely to learn when they received appropriate scaffolding from an adult (see also Nir-Gal & Klein, 2004). Clements and Sarama (2011) reported that a mathematics program for preschool children that included both on- and off-computer tasks was successful in enhancing foundational mathematical concepts (e.g., counting, adding and taking away, shape and geometric concepts) at school entry (Sarama & Clements, 2009). The results of a media-rich literacy intervention with preschoolers had positive impacts on children's ability to recognize and sound out letters and words and on their understanding of story and print compared with control children (Penuel et al., 2011). A series of studies by Bus and collaborators (e.g., De Jong & Bus, 2004; Kegel & Bus, 2012; Smeets & Bus, 2012, Smeets & Bus, 2013, Smeets & Bus, 2014; Verhallen, Bus, & de Jong, 2006) showed that electronic books can be more effective than traditional paper books in teaching pre-reading and vocabulary skills to preschoolers, especially those at risk for reading delay (e.g., low SES; second language learners). However the success of these e-books depends critically on a variety of pedagogical and design factors that support the content of the story as well as on the maturity of children's executive function skills (e.g., see also Collins, 2010; Korat, 2008; Miller & Warschauer, 2014; Moody, Justice, & Cabell, 2010; Shamir & Baruch, 2012; Smeets & Bus, 2012). In a related study, Tare, Chiong, Ganea, and DeLoache (2010) showed that 2- and 3-year-olds learned more facts and new words from a storybook with realistic images than children who were read the story with manipulatives (e.g., pop-ups) added.

With young children's increasing use of keyboards to drive their games and devices, there is a risk that typing may come to supplement or replace printing and cursive writing. However, there is evidence from neuroimaging research that the motor activity involved in printing letters facilitates emerging literacy skills such as letter recognition and that this perceptual-motor experience is evident in a specific pattern of brain activation in a "reading circuit" that includes anterior cingulate, fusiform gyrus, and the inferior frontal gyrus (James, 2010; James & Engelhardt, 2012; Kersey & James, 2013). These activations were not noted in children who used keystrokes to produce letters or who simply observed others do so. Though cautions in the use of technology with young children are clearly warranted, evidence-based usage holds the potential to enhance emerging computer skills and to foster an approach to problem solving that prepares young children to take their place in a multitasking world. However, additional well controlled studies on the effectiveness of these programs and on the new wave of available "apps" that ostensibly teach concepts and skills to toddlers and preschoolers are urgently needed. This is especially important as these young children have just emerged from the *video deficit* (i.e., their difficulty in imitating from video models although they readily imitate the same actions viewed live), but their understanding of the representational nature of screen media and their control of their attention are still very tenuous (see Barr, 2010).

Modelling multitasking behaviour

The extensive literatures on dual-task interference and on task-switching all indicate that (with few exceptions) there is a performance cost in speed and accuracy when these multitasking strategies are examined either in formal experimental procedures or in everyday work and learning contexts.

Even when the modalities and physical resources required to do the tasks do not overlap (e.g., visual/manual; aural/vocal) there is competition for a cognitive or procedural resource that diminishes performance on one or both of the tasks. These literatures also indicate that given the combinations and diversity of tasks that are required and the variety of cognitive, biological, social, and task-sequencing variables that can be involved, specifying the extent of interference in any given situation will be problematic. As the demand for multitasking continues to increase, researchers have developed cognitive models that attempt to quantify task interference and to predict performance. Some of these models were designed to describe specific tasks or sub-tasks and others were developed to describe multitasking more generally (e.g., Adler & Benbunan-Fich, 2012; Altmann & Trafton, 2007; Anderson, 2007; Borst et al., 2010; Horrey et al., 2006; Horrey & Wickens, 2004; Liu, Feyer, & Tsimhoni, 2005; Logan & Gordon, 2001; Meyer & Kiernas, 1999; Monk et al., 2004; Salvucci & Taatgen, 2008; Tombu & Jolicoeur, 2002; Wickens, 2002; Wickens, Goh, Hellenberg, Horrey, & Talleur, 2003).

The most recent attempts to model complex multitasking have relied on computational models in which task components and their resource requirements were identified and then specified formally as computer simulation that could generate the behaviour of interest (see Salvucci & Taatgen, 2011). These simulations were usually derived from a particular cognitive architecture – a working theory of human cognition based on experimental data and implemented in a computational framework (Byrne, 2008; Mulholland & Watt, 2005). The architecture incorporates and represents both the skills and limitations of human cognition (e.g., memory and forgetting processes, perceptual resources, motor resources). Given any task domain, the architecture allows for the specification of a model that performs the task, typically through interaction with a realistic simulation of the task, such that the behaviour of interest can be visualized, analysed, and validated against human performance on the same tasks.

Cognitive architectures provide a viable mechanism for simulating human multitasking as they can provide an integrated account of a range of task using a common set of principles. As an example, ACT-R (Adaptive Control of Thought – Rational) (Anderson et al., 2004) is a widely used cognitive architecture that is based on the Anderson and Bower (1973) theory of human associative memory and their model of it (HAM). ACT-R is a rule-based system that models cognitive activity as an explicit set of *production rules* (or productions) and it has been successfully used to model a wide range of behaviour in experimental and everyday domains involving memory, problem solving, and skill learning. The ACT-R formulation includes major cognitive (e.g., declarative memory, problem state, goal representation), perceptual (e.g., vision, audition) and motor (e.g., speech; movement) resources that are characteristic of the human system. Especially important is a central procedural (cognitive) resource that coordinates the other resources to initiate behaviour. A key feature of ACT-R is the distinction (and interaction) between declarative memory (information we know) and procedural memory (things we know how to do). In the model, declarative memory is the primary resource that stores information as related chunks of knowledge but also accounts for the impact of processes such as rehearsal, decay, forgetting, and neural activation on performance (see Salvucci & Taatgen, 2011). Procedural memory stores the production rules that provide a formula for how the model should behave. Knowledge is transferred from declarative to procedural memory in a process called *production compilation* that enables new rules to be created during practice and learning. Anderson and colleagues have used fMRI to establish a neural mapping between ACT-R processing resources used in certain tasks and specific brain regions.

Salvucci and colleagues (Salvucci, 2006; Salvucci & Gray, 2004; Salvucci & Taatgen, 2008, 2011) developed a theory of multitasking called "threaded cognition" that is embedded in the ACT-R framework. Threaded cognition holds that streams of thought can be represented as independent "threads" of processing coordinated by a procedural resource without the need for task-specific executive processes. Simple tasks (e.g., typing a string of numbers) can be represented as a single thread while complex tasks (e.g., driving) may be represented by multiple threads that work towards a higher-level goal, with each thread responsible for a subtask component. This implies that individuals have a core ability to interleave (or thread) the execution of multiple tasks concurrently or sequentially and makes the approach appropriate to explain multitasking. Threaded cognition implies that people can start, execute and stop threads of behaviour to adapt dynamically to any task environment. At the same time, core limitations in cognitive processing result in interference in certain situations and for certain combinations of tasks. By instantiating the theory of threaded cognition in the ACT-R architecture, explicit predictions can be made about how multitasking behaviour can result in interference (or not) for a given set of tasks. Threaded cognition has been used to account for dual-task interference in a number of laboratory and complex everyday tasks that are performed concurrently and also for examples of sequential multitasking in which task-switching is required (e.g., driving with and without in-vehicle distractions, aircraft manoeuvring, game playing). The value of these models lies in their potential to predict the degree of interference that is likely to occur in a wide range of activities. Such information will also be useful in designing work and learning environments that will minimize concurrent task interference and optimize multitasking performance (see Horrey & Wickens, 2004; Horrey et al., 2006; Salvucci & Taatgen, 2011).

An important question is the extent to which models such as threaded cognition can account for developmental and other individual differences in multitasking. According to Salvucci and Taatgen (2011), threaded cognition operates at the level of neural "hardware", the fundamental components of the perceptual, motor, and cognitive systems that are basic to human information processing. In modelling terms, the hardware corresponds to the cognitive architecture with its core abilities and constraints. As such, children are born with the potential to execute and interleave multiple threads although immaturities in their neural hardware will presumably limit those processes. One such limitation is in speed of processing, considered to be a "cognitive primitive" of the human architecture and a strong predictor of efficient performance in a range of task domains. Differences in speed vary in regular ways with age such that young children and older adults are generally slower to encode and process information. This affects task performance by limiting how much (or how quickly) information can be handled at any one time (Kail & Salthouse, 1994). In contrast, "software" differences that could affect multitasking arise from differences in declarative and procedural knowledge that occur as a consequence of individual differences in age and experience (see Bjorklund, 1987). In modelling terms, software refers to the knowledge added to the basic architecture that specifies the skills for a particular task domain. There are significant differences in the structure and content of children's knowledge with age that affect how they encode information as well as in what and how they recall. There are also marked developmental differences in both declarative and procedural memory that presumably affect production compilation and hence children's ability to interleave and execute threads (i.e., to multitask). In sum, with age, children encode information more quickly, process and store it in a richer knowledge base, and retain it for longer periods of time. In order to provide a viable developmental account of multitasking, age differences will have to be accommodated into the cognitive architectures upon which computational models are based.

Developments in attention: some basic processes

To date much of the literature on multitasking has focused on older children, adolescents, and adults. There is a general consensus that infants and pre-schoolers do not multitask, or do so poorly, as their attentional resources are severely limited. However, there are three general aspects of attention that change markedly across infancy and the early childhood years; visuo-spatial orienting, sustained attention, and endogenous or executive attention (see Colombo, 2001; Ruff & Rothbart, 2001; Richards, 2001; Rueda, Posner, & Rothbart, 2005). Developments in these attention processes are evident in a wide range of behaviours and also in the underlying brain structures and neurochemical systems that mediate them. They will also have a significant impact on whether and how infants and young children will attend to and process information during play, learning, and social interaction.

Visuo-spatial orienting

Ruff and Rothbart (2001) described infants' visual behaviour during much of their first year as dominated by an *orienting/investigative system* of attention. This includes a spatial *orienting* network (the posterior parietal cortex and subcortical systems such as the superior colliculus, pulvinar, and locus coeruleus in the brain stem) that is alerted by peripheral stimuli and directs attention to potentially important locations in the environment ("where" an object is). This network mediates attention functions such as, engagement, disengagement, and shifting. A second network governs *object recognition* (including the dorsal and ventral pathways from the primary visual cortex to the parietal cortex and inferior temporal cortex) that mediates attention to object features and gathers detailed information (e.g., form, colour, pattern) needed for object identification ("what" an object is). Infants also attend preferentially to certain stimuli though the basis of this selectivity is unclear (Fantz, 1964). Ruff and Rothbart (2001) suggested that a developmental transition in the structure and function of the orienting/investigative system from 3 to 9 months enables infants to deploy their attention flexibly and quickly and to respond to objects and events by their novelty or complexity rather than by their salience.

Sustained attention

A major advance that contributes to (and results from) this transition is the infant's ability to sustain attention on a selected stimulus. Sustained attention to object features (also called focused attention), is the extended selective engagement of a behaviour system that primarily enhances information processing in that system (e.g., see Richards, 2004; Ruff, Capozzoli, & Saltarelli, 1996). Sustained attention is measured by the duration and pattern of looking towards a stimulus and also by the correlated and extended deceleration of heart rate during prolonged looking. Infants as young as 3 months will engage in 5–10 s periods of sustained attention and the duration increases to several minutes or more over the first 2 years (Reynolds & Richards, 2007; Ruff & Capozzoli, 2003). Many of the infant's cognitive and social activities (e.g., learning, memory, play) occur during focused or sustained attention (see Hunter & Richards, 2003; Oakes & Tellinghuisen, 1994; Reynolds & Richards, 2007; Richards, 1997; Ruff & Rothbart, 2001). Advances in sustained attention are related to the development of brain systems controlling arousal and state, including the neuroanatomical connections between the mesencephalic reticular activating system, the thalamus, and the cortex (Richards, 2004).

Endogenous or executive attention

At the end of the first year, the rudiments of another attention system appears, one in which infants begin to acquire endogenous or voluntary control over the allocation of cognitive resources. Their look durations to simple objects decline whereas their looks to complex objects increase (Courage, Reynolds, & Richards, 2006; Ruff & Saltarelli, 1993). They look more to their caregivers in situations that call for social referencing (Rochat, 1999) and joint attention (Carpenter, Nagell, & Tomasello, 1998) and they begin to show behavioural inhibition on the A-not-B task (Diamond, 1985). Further evidence of emerging intentionality is evident in improvements in deferred imitation (Barr & Hayne, 2000), means-end problem solving (Willatts, 1997), and recall memory (Bauer, 2007). Towards the end of the second year this endogenous control of attention shows an increasingly executive function as toddlers and preschoolers begin to evaluate their behaviour, direct activity with goals and plans, and override more automatic thoughts and responses. These achievements are essential cognitive prerequisites for the concurrent and task-switching activities required for everyday multitasking in older children and adults. In this timeframe young preschoolers begin to understand dual representation and the symbolic nature of video material (DeLoache, 2000; Troseth, 2010). Several recent reviews of the literature concur that although there are precursor indices of executive functions from infancy, it is not until the preschool years that they made a significant developmental advance that continues to mature across later childhood and adolescence (Best & Miller, 2010; Garon et al., 2008; Wiebe et al., 2011). As these cognitive resources are fragile in young children, caution should be used in structuring learning and play environments that draw upon them. Developments in executive attention are closely related to brain activity in the prefrontal cortex, anterior cingulate, and frontal eye fields (e.g., Bell & Fox, 1994; Chugani, 1994; Huttenlocher, 2002; Posner & Peterson, 1990).

Developments in attention: challenges for young children in a multitasking world

Distractibility during play and learning

One consequence of immature executive functions is that young children are highly distractible. Given the number of external and internal events to which they are exposed, the ability to direct and sustain attention selectively to some stimuli (e.g., toys) while resisting distraction from others that compete for their attention (e.g., television) is critical for early learning. Indeed, parents, developmental scientists, and practitioners have expressed concern that the omnipresence of television (especially background television) and other screen media in the home might distract infants and young children from play and other activities (Courage, Murphy, Goulding, & Setliff, 2010). Research has shown that distractibility decreases across infancy and early childhood, although several endogenous (e.g., attentional state, engagement with the object) and exogenous (e.g., target salience or novelty, continuous or intermittent presence) factors interact with age (Kannass & Colombo, 2007; Kannass, Colombo, & Wyss, 2010; Oakes, Kannass, & Shaddy, 2002; Oakes, Tellinghuisen, & Tjebkes, 2000; Richards & Hunter, 1997; Ruff & Capozzoli, 2003; Ruff & Rothbart, 2001).

Background television is a significant source of distraction to young children at play as its formal features are salient, often novel, and come to signal interesting content. A recent survey showed that children under 2 years of age are exposed to about 332 minutes of background television a day (Lapierre, Piotrowski, & Linebarger, 2012) with the amount dropping to 163 minutes by age 8 years. Setliff and Courage (2011) reported that 6-, 12-, and 24-month-olds who were engaged in toy play spent less time attending to the toys when the television was on compared with when it was off (also see Schmidt, Pempek, Kirkorian, Lund, & Anderson, 2008). Children shifted their gaze from the toys to the television about three times per minute, though 46% of the looks were less than 2 s duration, likely too short for much information processing. However, it may be that as with older children (Lorch, Anderson, & Levin, 1979; Lorch & Castle, 1997), infants were engaged in an active and deliberate viewing strategy of monitoring the television rather than simply being distracted by it (Hawkins et al., 1997; Huston & Wright, 1983). Setliff and Courage (2011) also found that the duration of children's focused attention decreased while the television was on. In contrast, Ruff and colleagues (Ruff & Capozzoli, 2003; Ruff et al., 1996) found a preservation of focused attention during infants' toy play in an intermittent distractor condition. They suggested that infants may have used lower level processes such as peripheral narrowing to resist distraction and maintain focus on a central activity. However, the background television in the Setliff and Courage study provided a continuous and varied source of distraction that may have provided more stimulation than the infants could tune out (Kannass & Colombo, 2007). Whether young children adapt to distractors with intensified focused attention or through selective monitoring is a complex and important question that will likely vary with age, task complexity, and motivation (Higgins & Turnure, 1984; Turnure, 1970). Finally, there is evidence that once preschoolers are interrupted from play, they return to it with more superficial engagement (akin to the resumption lag in adults' task switching) than before the distraction (DiLalla & Watson, 1988).

Noisy environments, learning, and play

In some circumstances young children engage in concurrent activities and maintain focused attention during background distraction (Anderson, Alwitt, Lorch, & Levin, 1979; Schmitt, Woolf, & Anderson, 2004). However, researchers have suggested that background television itself (i.e., as a source of noise) might interfere with cognitive processing (e.g., Armstrong & Greenberg, 1990; Anderson & Evans, 2001). Evidence from observational studies indicated that chronic exposure to loud or moderate background noise (e.g., aircraft, traffic, construction) affected letter–number–word recognition, reading acquisition, memory encoding, visual search tasks, and stress levels in school children (e.g., Evans, Bullinger, & Hygge, 1998; Evans, Lercher, Meis, Ising, & Kofler, 2001; Evans & Maxwell, 1997; Lercher, Evans, & Meis, 2003; Maxwell & Evans, 2000), although the effects appeared to be reversible once the noise source was removed (Anderson, Bucks, Bayliss, & Sala, 2011; Dockrell & Shield, 2012; Hygge, Evans, & Bullinger, 2002; Maxwell & Evans, 2000; Shield & Dockrell, 2003). To examine this more closely, Jamieson, Kranje, Yu, and Hodgetts (2004) presented kindergarten and elementary school children with words that were mixed digitally with either 0, –6, or –12 db noise. Overall accuracy in word recognition decreased as signal-to-noise ratio increased. Hygge (2003) found that 10- to 12-year-olds' long-term recall of prose passages in conditions of simulated aircraft, road traffic, and vocal noise was poorer than that of control children who learned in noiseless conditions. There was a smaller impact on recognition memory, suggesting that noise during encoding might have produced a shallower level of processing compared with quiet conditions. Other studies examined performance under noise conditions that approximated a typical classroom. For example, Howard, Munro, and Plack (2010) showed, using a dual-task experiment, that considerable listening effort was needed to perform effectively at signal-to-noise ratios that were typical of many classrooms (see also Flagg-Williams, Rubin, & Aquino-Russell, 2011). Dockrell and Shield (2006) reported that 8-year-olds' reading and spelling were poorest in a babble (mixed background conversations) condition than in a no-noise condition. The mechanisms through which noise levels in the typical classroom might lead to diminished performance include masking, interference, divided attention, or increased arousal or cognitive load as children try to process information. These facts may be important in designing the multimedia and multitasking environments that are being incorporated into school curricula.

Although there are few studies on the impact of noise on learning in infants and toddlers, there are some suggestions in related literatures that they might also be negatively impacted by sources of noise during learning. For example, in addition to the omnipresence of television and electronic media in the modern home (Rideout & Hamel, 2006), additional noise comes from the growing availability of "noisy" toys that present young children with a diversity of concurrent stimulation from the sounds, sights and movements that comprise their function (McPake, Plowman, & Stephen, 2013; Singer, Golinkoff, & Hirsh-Pasek, 2006). Several studies have examined the effects of adding sound stimuli, music, or background multi-talker noise to an infant learning task. Barr, Wyss, and Somanader (2009) demonstrated a learning deficit after a 24 hour delay when brief, cartoon-like, synchronous electronic sound effects were added during the demonstration phase of a deferred imitation task with 6-, 12- and 18-month-olds. In another study, Barr, Shuck, Salerno, Atkinson, and Linebarger (2010) added related, child-friendly background music to a live or video demonstration on a deferred imitation task. Imitation after 24 hours was above baseline for the live model groups but not for the video groups (i.e. a video deficit) regardless of age. When both music and sound effects that matched to the actions in the video were added to the demonstration, performance was above baseline at all ages, though not better than a no-music video condition. It seems that adding music or sounds to a learning task, whether by live or video modelling, may have increased cognitive load and disrupted selective attention to the target actions (also see Smeets & Bus, 2014). An important message is that contrary to parental expectations and manufacturers' claims, adding even simple sound effects to electronically enhanced toys might diminish rather than enhance their learning potential (Singer et al., 2006). These findings are consistent with research on older children and adults in which adding redundant information to video material resulted in poorer recall of the target information (Bergen et al., 2005; Mayer et al., 2001).

Interestingly however, Newman (Barker & Newman, 2004; Newman, 2003, 2005, 2011) conducted a series of studies that showed that in the language domain, infants and young children are adept at filtering out signals from noise. For example, parents have reported that when they talk to their infants they frequently do so against a backdrop of other conversations. In spite of such noisy linguistic (i.e., multi-talker) environments, infants readily compensate by filtering their caregivers' voices from those of others and learning to identify streams of language that are relevant to them, such as their own name. Cues that infants use to do this include familiarity with a voice, spatial location, or visual cues (speaker looking at them). Rost and McMurray (2010) showed that adding multi-speaker noise (e.g., many speakers saying the same word) facilitated word learning as the variability provided by the many spoken versions assisted the process of generalization. However, language learning in general appears to be a privileged cognitive domain that prepares infants from birth to preferentially process information that is unique to human language acquisition (e.g., Kovacs & Mehler, 2009a, Kovacs & Mehler, 2009b; Sebastian-Galles et al., 2012). Such adaptations to noisy language environments may not generalize to noise more generally.

In sum, the literature from observational and experimental research indicates that background noise generally distracts young children from play and learning, increases their cognitive load, divides attention, and diminishes task performance. With this information and the evidence that background noise can disrupt cognitive activity in older children, the conditions under which young children might be able to adapt to noisy, distracting environments and to continue processing information should be documented.

Multitasking, learning, and the brain

Although competition for perceptual, motor and cognitive resources will affect the conditions under which multitasking can or cannot be done, it is important to consider the type of learning that occurs in single and multitasking conditions as well as the brain regions that support these activities. There is a concern that when individuals are engaged in multitasking, their learning is more superficial and less well integrated into their knowledge base compared with single-task learning. The latter situation ostensibly permits time for reflection and critical thinking, whereas the former promotes paying continuous partial attention to several concurrent activities while focusing on none of them in detail (see Carr, 2010; Greenfield, 2009; Rosen, 2010). Though there is no simple answer, there is evidence from animal and human clinical literatures that different forms of learning and memory depend on functionally and anatomically separable neural circuits (Squire & Wixted, 2011). Declarative (or explicit) memory supports the acquisition of information that can be consciously recalled and flexibly applied. The medial-temporal and hippocampal brain regions sustain declarative knowledge. Nondeclarative (implicit or procedural) memory supports incremental habit and skill learning that is not accessible to conscious recollection. This less flexible knowledge is supported by the striatum and other deep nuclei of the brain. Whether these two streams reflect multiple memory systems or a unitary system with multiple routes of access is unclear, though the debate is not directly relevant to the issue at hand (see Rovee-Collier, Hayne, & Colombo, 2001; Tulving, 1985). Regardless, the important question is how these two aspects of learning and memory might be differentially engaged in single and multitasking activities.

There is evidence from behavioural and brain activation research that multitasking may be associated with procedural rather than declarative learning. Foerde, Knowlton, and Poldrack (2006) had college students learn a weather prediction task singly or in the presence of a distracting secondary tone-judgement task. Dual-task conditions did not reduce performance accuracy but did reduce the amount of declarative knowledge participants had about the cues they used to predict weather during the task. Corresponding data from fMRI measures showed that medial temporal lobe activity was associated with single-task performance, whereas the dual-task condition showed greater striatal activity. So while the overall amount of learning during multitasking might not be less, it may be less richly connected in the knowledge base and may be less flexibly applied in new situations. Consistent with this, college students who studied science material with background television showed relatively poorer recall but not poorer recognition of the material than those who studied without distraction (Armstrong & Chung, 2000). One explanation was that although interference from the television during encoding might have made the information less organized and accessible for later recall, the information was available through simpler recognition processes that did not require a search of the knowledge base at retrieval.

There is also evidence that practice with ICT platforms more generally can facilitate efficient information seeking and that the effects are evident in altered patterns of brain activation. Small et al. (2009) showed that "net naïve" adults had a more restricted pattern of brain activity in the dorsolateral prefrontal cortex (DLPFC) during an Internet search for information (but not during a reading task) than did a matched group of "net savvy" adults. After 5 days of practice, the "net naives" showed the same extended pattern of activation as the "net savvy" participants. However, Sparrow et al. (2011) showed that students who used the Internet to search for answers to complex questions and who believed that the Internet would continue to be available at test, relied on that platform as a form of "external memory storage" rather than storing the information internally in their own memory for later recall. The widespread adoption of such a recall strategy among heavy Internet users might have significant implications for the structure and content of their knowledge base. This might be especially significant during early development when children's knowledge base is being newly established, an acquisition that is essential for cognitive development more generally (Bjorklund, 1987).

A recent and growing literature indicates that practice with action video games can have a positive impact on attention and brain networks. In many ways these games are a good model of everyday multitasking as they provide information from multiple input sources, involve complex visual scenes with several goals at different time scales, and require the coordination of memory tasks (spatial, semantic), executive function tasks (resource allocation, decision-making), allocating visual attention (tracking, detection, shifting), and visuomotor skills (steering, manoeuvring). Bavelier and collaborators (Bavelier et al., 2010; Bavelier, Green, & Pouget, 2012; Dye, Green, & Bavelier, 2009a, 2009b; Green & Bavelier, 2003, 2007, 2008; Green, Sugarman, Medford, Klobusicky, & Bavelier, 2012) conducted a series of experiments that showed a number of positive effects on aspects of vision, attention, cognition and motor control from their use. For example, compared with non-gamers, practiced action video gamers showed better visual acuity, contrast sensitivity, visual working memory, selective attention, localization accuracy, recovery from attentional blink, and tracking moving objects. Gamers were more efficient on task-switching and dual-task performance and showed faster processing speed on attention tasks without compromising accuracy, than did non-gamers. Importantly, providing training to non-gamers led to an improvement in their performance on attention tasks (e.g., visual search) that persisted and generalized to other non-gaming tasks. Most of this research has been done with young adults as action video games typically have violent content that precludes training studies with children. However, several studies based on self-report data showed that like adults, children as young as 6-years-old who were avid gamers also showed enhanced attention and visual processing skills (Dye & Bavelier, 2010; Dye et al., 2009a; Trick, Jaspers-Fayer, & Sethi, 2005). Possible mechanisms that underlie these achievements include changes in attentional bottlenecks, greater connectivity across and within the brain regions involved, or more efficient central task management that fosters a more general ability to gather information (Green & Bavelier, 2012). For example, a recent brain imaging study showed that gamers who performed a visual search task under high and low load conditions not only out-performed non-gamers but showed less neural activation in a fronto-parietal network known to control the allocation of attention. This suggested that with increasing task difficulty gamers allocated attention resources more automatically and effectively than non-gamers (Bavelier, Achtman, Mani, & Focker, 2012. The researchers cautioned that not all video games meet the criteria for "action video games" and are not equal in their task requirements or in their potential to alter human perception and cognition (Bavelier, Green, & Seidenberg, 2013; Green, Li, & Bavelier, 2010).

Other studies on neurocognitive activity during multitasking have used neuroimaging and electrophysiological techniques to test hypotheses about the brain's use of its resources during single and multitask performance. For example, there is evidence that in certain multitasking conditions additional cognitive and neural resources can be recruited from prefrontal executive areas, whereas in other conditions the brain shows only task specific increases (or sometimes decreases) in activation, depending on the need for resource sharing (D'Esposito et al., 1995; Jaeggi et al., 2003). Not surprisingly, the results of a growing literature indicate that the particular location, amount, timing, and patterns of activation observed depends on the requirements and automaticity of the tasks involved, on practice with the tasks, and to a lesser extent, on individual differences. Although there is still much to be learned, several general finding seem to be clear. First, when two tasks draw on common resources (i.e., cortical areas) the activation associated with a given task decreases when a second task is performed concurrently (e.g., Klingberg & Roland, 1997). Second, when two tasks with different input modalities (i.e., non-overlapping cortical areas) are performed concurrently but afford an opportunity for task switching (even briefly), a significant increase in DLPFC activation is observed in the dual but not the single-task condition. For example, Watson and Strayer (2010; Strayer & Watson, 2012) reported that a small group of "supertaskers" who were able to perform concurrent tasks without interference showed less brain activation than did non-supertaskers in cortical areas (frontopolar prefrontal, dorsolateral prefrontal, anterior cingulate) known to be important for multitasking (Burgess et al., 2000; Shallice & Burgess, 1991).

Third, when the tasks to be performed involve two concurrent sources of input that cannot be switched, activation in the areas that are required by each of the tasks individually decreases from the single to the dual-task condition. As an example, Just et al. (2001) used fMRI to measure cortical activation during the concurrent performance of two cognitive (mental rotation, language comprehension) tasks that involved different sensory modalities (auditory, visual) and activated largely non-overlapping areas of sensory and association area cortex. They found that in the dual-task condition the activation in the association areas was substantially less than the sum of the activation when the two tasks were performed singly, suggesting some amodal mutual constraint between the association areas. The finding was replicated in an everyday task involving driving and language comprehension. When those tasks were performed together, driving performance decreased as did activation in the parietal cortex associated with spatial processing (Just et al., 2008). Consistent with this, when tasks are automatic (or become so through practice), additional executive brain areas are not recruited; rather there is increased activation in task-specific areas involved in the single tasks (Dux et al., 2009). Buchweitz et al. (2012) confirmed this using fMRI with a few rare students who were able to listen to and comprehend two streams of conversation at the same time. Performance of the two language tasks concurrently did not result in additional activation of DLPFC, but did show additional activation in task-specific processing areas. There was also increased functional connectivity among the language areas of the brain in a dual-task (two speakers) compared with a single-task (one speaker) condition. Prakash et al. (2012) reported that students who were trained on complex video games not only performed better than untrained controls but also showed reduced activation in attention control areas (right middle and superior frontal gyrus, ventromedial prefrontal cortex) and in motor and sensory cortices of the brain as the tasks became more practiced and automatic (also see Gentile, Swing, Anderson, Rinker, & Thomas, 2014; Maclin et al., 2011; Kelley & Yantis, 2010).

What this body of literature indicates is that while the brain may be poorly designed to process multiple simultaneous sources of input, it appears to be well designed to try to adapt to whatever task conditions that the environment provides. This could mean the encoding and storage of information in a way that preserves learning but diminishes its flexible use in other contexts, or recruiting additional executive brain resources to coordinate simultaneous task demands, or deferring one of the tasks until capacity is freed up or the bottleneck is cleared. It also indicates that the brain is remarkably flexible and responsive to conditions of training and that action video games (and perhaps non-action games and ICT platforms) may be a effective tools to explore the limits of plasticity in attention and learning systems (see Posner, 2012).

Conclusions: what do we know?

The fundamental challenge in understanding human multitasking has been to make explicit a set of common core principles that hold across the diversity of tasks, contexts, and individuals for whom this work, learning, and play strategy has become a way of life. The task is complicated by the fact that “multitasking” and “technology” are not unitary constructs and the particular tasks and technologies involved in any set of activities will affect performance in very different ways (Adler & Benbunan-Fich, 2012; Bavelier et al., 2010; Greenfield, 2009; Judd, 2013). However, only with some consensus will researchers be able to develop theories and models that can answer questions concerning when and for whom multitasking will be successful and when and for whom it will lead to interference, diminished capacity, and poor performance. The literature reviewed here indicates that much is still to be learned, although several important things are fairly clear.

Multitasking is generally less efficient than single-task performance

The classical experimental literature indicates clearly that across a wide range of tasks, and with a very few exceptions (e.g., see Buchweitz et al., 2012; Watson & Strayer, 2010), multitasking performance is less efficient (i.e., time, accuracy) than is single-task performance. For everyday multitasking, in which task juggling can be at the discretion of the individual, performance accuracy is not necessarily impaired, though task completion times will likely increase. This should not be underestimated as many contemporary work and learning assignments are time constrained and for some, “time is money”. Given that multitasking is here to stay, the best strategy will be optimize performance under those conditions by identifying the components of the tasks to be completed and coordinating the relevant perceptual, cognitive, and motor resource demands to minimize interference. To some extent, the perceptual (e.g., visual, auditory) and motor (e.g., oral, manual) components that serve as channels through which cognition interacts with the external environment can be readily identified and controlled. Two concurrent tasks that require the visual resource (e.g., looking at the road, reading) or a common manual response (e.g., pressing keys, steering) will have to share the resource and performance will suffer. In contrast, the more intangible cognitive resources can be difficult to specify and apportion across tasks. Cognitive resources are complex and must be shared during many activities even where there is no obvious perceptual or motor overlap, such as in reading and listening to a conversation or talking on a cell phone while driving through traffic. In the language of Anderson's ACT-R cognitive architecture (Anderson et al., 2004), a key cognitive resource is declarative memory where information for problem solving and task performance (including the problem state) is stored. As this memory resource is subject to normal encoding, storage, and retrieval processes, it can disrupt performance if task demands (e.g., rehearsal, reconstruction) on declarative memory conflict or overlap in time. Likewise, the central procedural resource that stores, coordinates, and executes the production rules needed to perform tasks, will be constrained by interference in declarative memory. Clearly, predicting interference among the combinations of tasks that individuals perform concurrently or sequentially on a daily basis is daunting. However, recent computational models (e.g., threaded cognition) have shown promise in providing detailed task analyses and in identifying principles of resource use and sharing that facilitated prediction and quantification of interference in a wide range of tasks. In addition, Rosen et al. (2010) contend that for many everyday situations in which children and youth of the "iGeneration" are multitasking as they work and learn, developing constructive new strategies that are compatible with (and build upon) their expertise with technology will ultimately optimize their productivity and satisfaction.

Children's immature attention and cognitive processes make multitasking difficult for them

The cognitive resources required for effective multitasking depend on being able to control and deploy attention, especially executive functions such as working memory, response inhibition, flexible task or set shifting, and metacognition. These cognitive skills are immature in young children and develop slowly across childhood and adolescence. Such limitations suggest that young children will likely not do well in multitasking situations either formally in "noisy" school settings or at home amid the concurrent sights and sounds of electronic media as they play and learn. This does not mean that children's facility with ICT should not be incorporated into their daily environments, but simply that they must be developmentally appropriate in form and function. Nor should it be forgotten that there is a large literature that indicates that young children learn more effectively in interactive settings with an adult or a peer than from any of the electronic media (see Barr, 2010). That being said, it may be the case that "digital natives" who have been born into the current noisy, high-tech, multitasking environment will develop adaptive strategies that allow them to focus on the task at hand and resist distraction effectively. Indeed, there is some evidence that even toddlers and preschoolers can intensify focused attention to their toys in the presence of a distraction during play (Ruff & Rothbart, 2001). Young children have also shown they could monitor the content of background television as they played with toys and were able to report details of the program content (Lorch et al., 1979; Lorch & Castle, 1997). Finally, there is recent evidence that executive functions can be enhanced in children through carefully designed training programs that foster self-regulation (Diamond & Lee, 2011; Posner, 2012). These studies raise intriguing questions for future research on children's adaptations to multitasking environments.

Multitasking per se does not damage developing attention and learning systems

There is no compelling evidence that multitasking (including media multitasking; action video gaming) per se causes deficits in developing attention processes (Ferguson, 2011). The essence of this persistent concern is that overexposure to technology might "re-wiring" children's brains, shorten their attention spans, and place them at risk for attention deficit hyperactivity disorder (ADHD). A serious problem in addressing this is the lack of clarity on what "re-wiring" actually means, as nowhere is the term operationally defined by those who use it. For some, it appears to equate with "learning" (e.g., Small & Vorgan, 2008), making it an unremarkable observation as learning from any source is reflected in brain activity at some level (see Brem et al., 2010; Keller & Just, 2009; Meyler, Keller, Cherkassky, Gabrieli, & Just, 2008; Rueda, Rothbart, McCandless, Saccomanno, & Posner, 2005). For others, "rewiring" seems to imply a more fundamental (though unspecified) alteration of the structures or synaptic connections in the neural networks underlying attention that distinguishes heavy from light multimedia users (e.g., Christakis & Zimmerman, 2005). However, to the extent that "action" video games reflect everyday multitasking, practice with those platforms can actually enhance certain vision and attention processes that are also observed in altered brain functioning. A similar definitional issue is that some studies state concern about "attention problems" in young children but these are often vaguely identified on the basis of self-report or teacher and parent observation rather that a formal diagnosis of ADHD (e.g., Swing, Gentile, Anderson, & Walsh, 2010).

In any event, similar concerns were expressed a decade ago about heavy television viewing and the consensus of the literature at that time left those particular concerns unsubstantiated (see Courage & Setliff, 2009). Research showed instead that major deficits in attention such as ADHD are attributable largely to neurobiological and genetic factors and to a lesser extent to biohazard exposure (e.g., alcohol, environmental contaminants) and to complications of pregnancy and birth, with social factors likely of minor importance (see Barkley, 2006; Rietveld, Hudziak, Bartels, & van Beijsterveldt, 2004). Although children with attention deficits do watch more television (and play more video games) than children without deficits, a causal connection between the two is not clear (Gentile, Swing, Lim, & Khoo, 2012; Swing et al., 2010). Instead, current evidence suggests that children with attention deficits are more likely drawn to action television and video games as the rapid pace and changing visual images of these media provide the elevated level of stimulation that these children seem to require (Ferguson, 2011). What may be of greater concern is the evidence that multitasking may be associated with procedural rather than declarative learning (Foerde et al., 2006). This suggests that for some types of multitasking, the brain appears to conserve resources by restricting the more advanced (declarative) learning and memory processes and relying on the more basic (procedural) ones. This finding is important as the thought processes that underlie scientific and critical thinking and imagination require the depth of processing and flexible declarative knowledge that comes from single task learning (Greenfield, 2009).

Neural plasticity may support adaptations to multitasking activities during attention and learning

Avid action video gamers performed better than their non-gaming peers on a range of tasks that require flexible allocation of attention resources and on tasks that measure the spatial and temporal aspects of vision. Moreover, non-gamers acquired these skills with training and the skills persisted and generalized to other tasks. The mechanisms and processes that underlie these advances are complex and are the focus of current research. However, they do appear to involve the top-down deployment of flexible attention processes that in turn enable a more general capacity to "learning how to learn" (Green et al., 2010). Moreover, the design of action video games incorporate features that foster effective learning more generally. These include the ratio of massed vs. distributed practice, individual difficulty levels, incremental learning, immediate feedback, and participant engagement and arousal, features that might also be effectively employed in the design of educational software (Green & Bavelier, 2012; Green et al., 2010). However, not all video games meet the criteria for "action" video games and should not be expected to produce the same enhancement in attention and learning (Green et al., 2010). For example, Franceschini et al. (2013) showed that 2 hours of playing action video games significantly improved reading and attention in 9-year-olds with dyslexia. Matched control children who were trained on non-action video games did not show parallel improvements. This does not mean that practice with "non-action" video games cannot also have positive effects on performance, simply that they will be different. Indeed, a variety of enhanced skills have been observed among avid gamers in paradigms that involved simulated everyday work activities (Kearney, 2005) and the skills for laparoscopic surgery training (Rosser et al., 2007). More recently, Li et al. (2013) showed that adults with amblyopia (i.e., reduced acuity in one eye following a disruption of binocular input during a critical period) who did not respond to conventional patching therapy showed improvement in visual acuity following several practice sessions with the (non-action) video game *Tetrus*. However, the mechanisms that underlie these improvements are not known and may lie in task specific processes rather than in more general attentional mechanisms.

The fact that action video games can have a positive impact on certain attention and learning processes does not imply a recommendation that children and youth play them for extensive periods of time. Indeed, the amount of time spent with all screen media is negatively correlated with academic achievement and success, likely because it displaces time spent in other activities that are essential for cognitive development and good health (e.g., reading; peer interaction, sports and outdoor play).

Also, the content of action video games is often violent and, as with excessive viewing of violent TV content, can contribute to increased aggressive behaviour and attitudes in some children (see Anderson et al., 2010; Ferguson & Kilburn, 2010). Finally, although there is no current standard for "excessive" action video game and Internet use, spending many hours with these media can place children and youth at risk for "addiction-like" behaviour that will have negative impacts on routine responsibilities and can lead to social isolation, anxiety and depression (Block, 2008; Gentile et al., 2011). In sum, what all of this evidence does confirm is that the brain changes and adapts in response to many types of experience throughout the lifespan. As neural plasticity is especially high during the early years, children may well be positioned to adopt new ways of learning in response to multiple sources of input that characterize their multitasking world (see Lillard & Erisir, 2011).

Research from neuroergonomics will facilitate effective multitasking

If multitasking continues to emerge as the preferred new order of learning and doing business, human factors engineers will need to use the information from basic research to design work and learning environments that optimize performance and minimize task interference under those conditions (see Horrey & Wickens, 2004; Salvucci & Taatgen, 2011). Advances and innovations in neuroergonomics, in which neuroimaging techniques are integrated with behavioural measures to provide analysis of person-work interfaces, will facilitate this goal. For example, the Just et al. (2008) fMRI study revealed that the parietal cortex that was activated by a driving task showed lower activation when done concurrently with a sentence comprehension task. The study not only provided evidence for the resource decrement (or capacity sharing) interpretation of multitasking but also potential policy guidelines for in-car technology design and use. Researchers have also used event-related potentials (ERPs) with behavioural measures to provide information for the mental workload assessments that are typically done when designing new human–machine systems or evaluating existing ones. Mental workload is a measure of how hard the brain is working to meet task demands. It can be measured independently from performance output to predict performance stability, decrement, or error and impending failure. For example, the P300 component of the ERP wave is reduced in amplitude when attentional resources are diverted away from target discrimination in dual task situations (Kramer & Parasuraman, 2007). Schultheis and Jamieson (2004) also used the method to assess the mental workload demand of a multimedia educational system that combined text, video and graphics and to make recommendations for optimizing the program.

The design of work environments will also be optimized using the tools and data provided by computational modelling of single-task and multitasking performance. Several such models derived from cognitive architectures and validated against data from human performance have been used successfully to predict interference and provided guidelines in a range of work situations (see Salvucci & Taatgen, 2011). Indeed, it is becoming evident that the research tools and techniques from the fields of neuroergonomics and computational modelling can be mutually beneficial as they begin to share the common rubric "computational neuroergonomics" (Liu, Wu, & Berman, 2012). Neuroergonomics, as a rapidly developing field, has generated a huge amount of empirical data as well as new concepts and technologies. Computational modelling can facilitate the summary, organization and interpretation of data, help guide system design by comparing design options and alternatives, and generating new hypotheses and directions for future research.

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