Failures Due to Interruptions or Distractions: A Review and a New Framework

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Interruptions of ongoing activities have spread since the development of and global increase in technology use and the general speeding in pace we all experience every day. Their negative effects are well known: decline in performance and emotional distress. However, the literature still needs to shed light on the exact cognitive mechanisms involved in the way users decide to reply to an interruption, on the effects of interruptions of different durations, and on factors influencing reactivation of task schemata and goals at resumption. Therefore, the aim of this article is to review the existing literature and models, uncover unresolved challenges, and propose new ways to confront them. We first review the substantive findings of recent decades from different domains (human–computer interaction, cognitive and experimental psychology, ergonomics), and their respective methodological and theoretical contributions. Then we propose a general and operationalized definition of an interruption; review the different cognitive models of attention, executive control, and working memory that best explain the impact of interruptions; describe current challenges and questions that remain open for future studies; and finally propose an integrative research framework, the DETOUR, which clarifies the cognitive processes at play during interruptions. We believe this work can directly affect the current state of the art, leading to new fundamental studies and applied solutions for the management of interruptions.

KEYWORDS: interruptions, distractions, attention, task switching, MFG model

Interruptions of ongoing activities have proved to be one of the hot topics in applied cognitive sciences, gathering researchers from a wide variety of specialties such as human–computer interaction (Bailey & Konstan, 2006; Roda & Thomas, 2006), cognitive psychology (Eyrolle & Cellier, 2000; Müller & Rabbitt, 1989), neuropsychology (Clapp & Gazzaley, 2012; Law et al., 2004), ergonomics (Ratwani, Andrews, Mccurry, Trafton, & Peterson, 2007; Salvucci, Monk, & Trafton, 2009), and management (Glasspool et al., 2007; Jett & George, 2003). Interruptions are known to divert the focus of our attention, forcing us into considering distracting events, unanticipated most of the time, sometimes at the cost of our precision and speed. Researchers have shown that in some specific cases, mostly when a lot of attention is needed to perform a task, interruptions can prevent the correct processing of stimuli, resulting

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sometimes in dramatic consequences. Famous cases of air traffic accidents or medical tragedies (Eyrolle & Cellier, 2000) were directly linked to interruption-related errors.

According to Reason's (1990) model of human error, interruptions can cause temporary lapses of attention and induce a particular type of error called omission following interruption. After one is interrupted, omissions (i.e., failures to complete a subtask of a set of action) can be more common because of mistakes during the resumption stage. Thus, knowing more about the cognitive processes involved during an interruption could have very positive impacts. First, from an applied perspective, it could help in developing new tools such as attention-aware systems (Roda & Thomas, 2006) to diminish the disruptive effect of interruptions (Bailey & Konstan, 2006; Ratwani et al., 2007). Second, in terms of more fundamental cognitive sciences, interruption research could also help reveal more about attention, task-switching, and working memory processes (Morgan, Patrick, & Tiley, 2013; Shum, Cahill, Hohaus, O'Gorman, & Chan, 2013). Therefore, the aim of this article is to review the existing literature and models, uncover unresolved challenges, and propose new ways to confront them. After summarizing most of what we know about this phenomenon, we will propose a new definition of an interruption with four specific criteria. Several attention and working memory models accounting for the effects of interruptions will be then presented, followed by a review of the existing models of interruptions. Finally, currently unsolved issues will be presented and a new research framework will be proposed.

Although most studies insist on the deleterious effects of interruptions on the ongoing task, a few studies reported benefits, whether on this task itself or on the overall time to complete the task. Adler and Benbunan-Fich (2013) suggested that self-interruptions (i.e., a type of interruption triggered by internal events) could have positive effects on creativity, especially when one is having difficulty solving problems, acting like an incubation moment (Beeftink, van Eerde, & Rutte, 2008; Dabbish, Mark, & González, 2011). Nonetheless, other studies suggested that self-interruptions, especially those oriented toward information and communication technologies (e.g., cell phones, social networks), could have negative effects on attention and memory processes (Rosen, Mark Carrier, & Cheever, 2013). Moreover, observational studies in work settings suggest that a large percentage of interruptions (40%) are self-initiated (Czerwinski, Horvitz, & Wilhite, 2004; Jett & George, 2003). Concerning the putative positive impact of interruptions, other researchers have proposed that, in some cases, the primary task is completed faster after resumption because of compensatory mechanisms (Burmistrov & Leonova, 2003; Mark, Gudith, & Klocke, 2008). Speier, Vessey, and Valacich (2003) suggested that an interruption occurring while one is doing a simple task might improve its completion afterwards by narrowing the focus of attention and facilitating decision making. On the contrary, interrupting a complex task might narrow the focus so much that less information is processed and crucial information is missed. This would deteriorate performance (Baron, 1986). Indeed, Ratwani, Trafton, and Myers (2006) showed that interrupting boring, repetitive, or simple tasks speeds up their execution, but this effect is not observed for complex tasks. Therefore, most of the time, interrupting a task decreases the general performance.

Several dependent variables have been used to show the effects of interruptions: task completion times, accuracy, and scores in scales of affective states (Bailey & Konstan, 2006). Among the task completion variables, the most represented is the time on task (TOT), that is, the total time spent on the primary task, excluding the time spent on the interruption. It is used to compare uninterrupted to interrupted trials. The inter-action interval (IAI) is also used as a measure of completion time of the primary task and has proved sensitive to interruptions (Brudzinski, Ratwani, & Trafton, 2007; Cades, Boehm-Davis, Trafton, & Monk, 2007; Ratwani et al., 2007, 2006). However, both these variables do not reveal much about the specific ongoing effects during the resumption stages. This is why the resumption lag (RL) has been proposed (Trafton, Altmann, Brock, & Mintz, 2003) and corresponds to the time necessary to resume the main task after an interruption. Accuracy has been reported in many experiments but seems less sensitive to interruptions (Bailey & Konstan, 2006; Botvinick & Bylsma, 2005; Foroughi, Blumberg, & Parasuraman, 2015). However, Reason (1990) suspected that omissions might increase after interruptions. The choice of which variables to use is very critical, because they do not reflect the same mental operations. For instance, the RL is a better indicator of the effects of variables on resumption processes, whereas the TOT can provide precious information about effects occurring afterward (Huber, 2015). Finally, declarative scales can be used to estimate the affective states of participants. Studies regularly bring up evidence that interruptions cause annoyance and anxiety (Altmann, Trafton, & Hambrick, 2014; Hart & Staveland, 1988; Mark, Gonzalez, & Harris, 2008; Spielberger, Gorsuch, & Lushene, 1983).

Before presenting a formal definition of an interruption, we first need to understand the cognitive processes involved in the main task. The human system is supposed to act as an information processing machine that transforms the perceptual signals into intelligent outputs. The success of such complex operations depends in part on the attentional systems that help select the appropriate action schemata in order to reach the goals (Norman & Shallice, 1986; Shallice, 2002). Action schemata are knowledge structures representing sensorimotor knowledge that constitute an action sequence (Davies & Logie, 1993), whereas a goal is a mental representation of the person's intention to accomplish a task and take some mental or physical action (Altmann & Trafton, 2002). Whether this purpose is conscious or not, goals are satisfied when the intended action is completed (Zhang, Pigot, & Mayers, 2004). Also, attention provides the necessary resources for the different processes to work properly. It has been long suggested that the amount of resources is limited (Kahneman, 1973; Wickens, 2008) and must be invested cautiously. When an interruption occurs, it triggers an alert, causing the disengagement from all the task-related goals and switching the focus of attention toward it. When the primary task that was interrupted is resumed, the reorientation of attention (Posner, Inhoff, Friedrich, & Cohen, 1987) and the reactivation of the goals (Monk, Trafton, & Boehm-Davis, 2008; Trafton, Altmann, & Ratwani, 2011) generally induce a global cost in speed and accuracy.

Definition of an Interruption

Several definitions of interruptions have already been proposed (Boehm-Davis & Remington, 2009; Jett & George, 2003; Mark, Gonzalez, & Harris, 2005; Speier, Vessey, & Valacich, 2003; Trafton et al., 2003), although some of them have not taken into account important factors. Also, *interruptions* have been used interchangeably with *multitasking*. However, multitasking is different from reacting to an interruption and refers only to the ability to perform several tasks within the same time period. Such operations can be performed in two different manners with different mechanisms involved: either simultaneously (dual-tasking) or sequentially by switching back and forth between the tasks (Darmoul, Ahmad, Ghaleb, & Alkahtani, 2015; Logie, Law, Trawley, & Nissan, 2010). This is why we think there is a need for a definition that encompasses every aspect of interruptions and differentiates them from other constructs. The occurrence of an interruption combines four unique criteria: a primary task is suspended temporarily; there is the intention to return to and complete it; the new task (i.e., interruption task) is introduced by an event, unanticipated or not; and the event can be either external or internal to the person. The introduction of such an interruption alert supposes a disengagement of attention from the primary task to perform the new one. Interruptions generate an interference with the ongoing goals maintained temporarily in working memory, inducing a cost in terms of speed and accuracy (Brumby, Cox, Back, & Gould, 2013; Gillie & Broadbent, 1989) and increasing the workload (Bailey & Iqbal, 2008; Wickens, 2008).

In their model, Trafton et al. (2003; Figure 1) focused on the temporal properties and proposed that interruptions can be divided into several stages: the interruption lag, that is, the time between an interruption alert and the beginning of performance of the interruption task, containing encoding strategies and task-switching processes; and the resumption lag (RL), that is, the time between ending the interruption task and resuming the primary task. Task-switching costs and processes involved in recovering the action schemata and context of the primary task can explain the duration of the RL.

McFarlane (2002) has proposed a taxonomy to illustrate the different response strategies one can apply to respond to an interruption that varies with the user's level of control: immediate (i.e., requiring an immediate response), negotiated (i.e., leaving the decision to the user), mediated (i.e., relying on an intelligent system that filters and supervises like

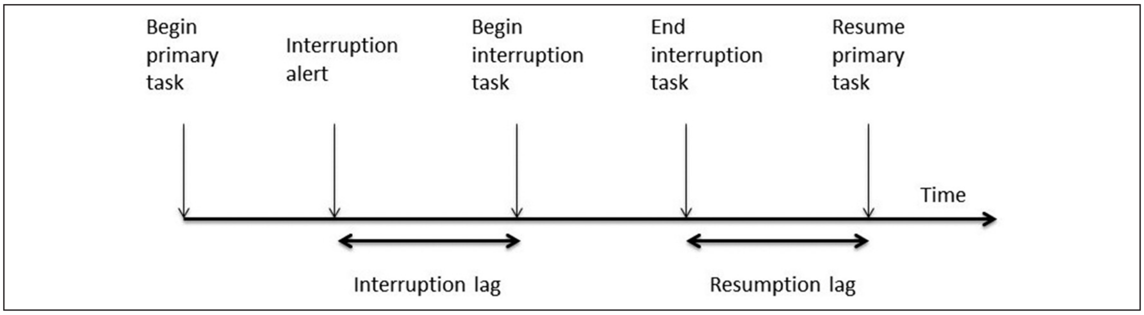

FIGURE 1. A typical interruption involves a primary and an interruption task. The sequence of events contains two phases. According to Trafton et al. (2003), the first phase, the interruption lag, contains encoding of the primary task and task-switching processes. The second phase, the resumption lag, contains also task-switching processes and reactivation of the components of the primary task

attention-aware systems; Bailey & Konstan, 2006; Roda & Thomas, 2006), and scheduled (i.e., expected). To this day, no model of interruptions has tried to incorporate these decision-making processes, although they appear critical in terms of potential error generation, especially in case of negotiated strategies.

Interruptions and distractions share common features and are often used interchangeably as representing both external and internal interferences (Boehm-Davis & Remington, 2009; Lin, Kain, & Fritz, 2013). They both involve a common starting point, which is a momentary disengagement of attention from the primary task and switching toward the alert. However, they involve different mechanisms afterwards (Jett & George, 2003; Lin et al., 2013). Interruptions involve supplementary mechanisms to support the maintenance of information and action schemata of the primary task, as well as using mechanisms for recovery after the interruption (Sakai, 2003; Sakai & Passingham, 2004). Other researchers have also proposed that interruptions require a more complete suspension of the ongoing task and some engagement on the interruption task (Boehm-Davis & Remington, 2009). A few electrophysiological studies have indeed shown that different cerebral networks could be involved in suppressing distractors and reacting to an interruption (Clapp & Gazzaley, 2012; Clapp, Rubens, & Gazzaley, 2010; Jett & George, 2003). Also, according to Clapp and Gazzaley (2012), distractions involve momentary lapses of attention on the primary task without an active engagement in the interruption task. But this definition remains unclear because even in that case the system has to process distractions to some extent to decide whether to respond to it or not. The distinction between pure distraction and interruption might therefore reside in the high-order processes that are involved afterwards (Clapp et al., 2010). Cognitive models of interruption should also take this into account.

Attention and Working Memory Models Accounting for the Effects of Interruptions

The following models have not been initially proposed to explain such effects, so they do not clarify all the results reported in the literature. A complete cognitive model should take into account all the different aspects proved to influence interruptions.

Attention processes are essential for actions and are likely to explain most of the effects found about interruptions. The limited attentional resources (Kahneman, 1973; Wickens, 2008) constrain the system to attend selectively to some stimuli and process them sequentially. An interruption will create an alert that will stop the flow of information processing then reorient the resources from the primary task toward the interruption task (Eyrolle & Cellier, 2000; Petersen & Posner, 2012; Posner & Petersen, 1990). Sustained attention allows maintenance of the correct amount of resources throughout the action (Head & Helton, 2014). Finally, there is a need to disengage from the interruption task once completed to reorient toward and resume the primary task.

Other mechanisms are needed to explain how attentional processes allow managing interruptions in terms of control of actions (Norman & Shallice, 1986). Routine actions require a minimum amount of resources to control for interference, whereas more resources are needed for novel or willed actions because they rely on deliberate processing. Different mechanisms are involved in these two types of actions, and therefore they are not susceptible to interruptions in the same ways. According to Norman and Shallice (1986), each highly routinized task is present in the cognitive system in the form of action schemata that could be activated at almost no attentional cost. When someone is doing multiple routinized activities at the same time, many action schemata are activated simultaneously, causing potential interference. The first system postulated by their model, contention scheduling (CS), would select the highest activation, generating the action and managing interference. Thus an interruption might result in selecting inappropriate action schemata, causing errors after resumption (Foroughi et al., 2015; Reason, 1990). By contrast, willed or novel actions need greater attentional control because the action schemata are either inappropriate or absent. It is thus necessary to adapt their behavior. A second system, the supervisory attentional system (SAS), is required in such situations that involved supervising, generating strategies, planning, and solving problems. It acts by modifying the activation value of the existing undesired action schemata, reinforcing or inhibiting the activation value, or creating new ones to attain goals and keep the interference level low. The SAS is also needed when action plans must be modified according to an unanticipated change, such as an interruption. When responding to an interruption, the SAS follows three stages: It constructs new temporary schemata, implements them, and monitors their execution. If the new action is successful, the new schemata replace the source schemata to provide a new procedure to deal with the action (Shallice, 2002). Therefore, interruptions could be less impactful because of greater flexibility.

Interruptions also imply switching between two tasks, that is, changing from one task to another. Such flexibility involves high-order cognitive processes (for a an extensive review, see Kiesel et al., 2010; Vandierendonck, Liefooghe, & Verbruggen, 2010). In task-switching experiments, participants usually have to perform several tasks in a row either in blocked conditions (repeated trials) or intermixed conditions (switch trials). When compared with repeat trials, performance in switch trials is usually decreased, showing a "switch cost" in terms of both speed and accuracy (Kiesel et al., 2010). Such a cost can partially explain the impact of interruptions on performance, especially on resumption measures. Two main theories posit the existence of specific processes responsible for the switch cost (Monsell & Mizon, 2006; Wylie & Allport, 2000). They both agree that the correct execution of a task requires the correct activation of schemata that specify the execution parameters. Simply put, preparing an action may consist in triggering the right schemata and storing them temporarily in memory during the execution of the task (Shi, Meindl, Szameitat, Müller, & Schubert, 2014; Vandierendonck et al., 2010). But the two theories differ in the explanation of the switch cost.

For the interference theory, it is due to schemata inertia, a proactive interference from previously activated schemata on the execution of another task (Wylie & Allport, 2000). In other terms, the switch cost would be explained solely by the requirement to inhibit the previous schemata. The second theory, the reconfiguration view, insists that the switch cost reflects the time needed to reconfigure schemata or retrieve them from long-term memory (Monsell & Mizon, 2006; Sohn & Anderson, 2003). This view assumes a distinction between task preparation and task execution processes. Factors that affect both processes (e.g., task difficulty, stimulus discriminability) do have additive effects on switching costs (Liefooghe, Demanet, & Vandierendonck, 2009; Rubinstein, Meyer, & Evans, 2001). In both cases, response inhibition and cognitive inhibition processes are strongly involved during task-switching phases to reduce the activation of the components related to the task participants are leaving. This is supported by empirical behavioral and electrophysiological findings (Mansfield, Karayanidis, & Cohen, 2012; Mayr, Kuhns, & Hubbard, 2014; Piguet et al., 2013). Threaded cognition models also predict that the ability to switch between tasks greatly depends on available cognitive resources (Salvucci & Taatgen, 2008). However, such models account for the results of concurrent multitasking (or dual-tasking) and do not address specific issues raised by interruptions. Finally, several studies have shown that switching cost can be influenced by factors such as mental preparation, training, or aging, which could influence interruption management as well (Cades, Trafton, & Boehm-Davis, 2006; Shum et al., 2013; Vandierendonck et al., 2010).

Other models are needed to understand what happens to the goals and action schemata of the primary task during the interruption. As stated by Altmann and Trafton (2007), they decay progressively as the interruption goes on. Their levels of activation directly influence the resumption processes. Current working memory models are consistent with this decline. For instance, Cowan's theory (Cowan, 1988, 2008) posits that working memory emerges from the activation operated by attentional mechanisms of traces contained in long-term memory. The components are activated as long as they are contained within attentional focus, but once it moves elsewhere, they decline to complete extinction within 30 s. Thus, an interruption longer than 30 s would completely extinguish the components related to the primary task. Once the interruption is over, they must be reactivated completely in order to resume that task. Even though this time window was not specifically investigated, different effects were reported for periods less than 30 s and those lasting longer. For example, Eyrolle and Cellier's study (2000) showed that, while their participants were executing the interruption task, they generated more errors during the first 30 s, presumably because of an interference between the primary and the interruption tasks. After that delay, this effect was not present anymore, suggesting that the schemata associated with the primary task were completely extinct. Seemingly, the 30-s windows might play an important role and should be investigated more thoroughly.

Another working memory model, the time-based resource-sharing model (Barrouillet, Gavens, Vergauwe, Gaillard, & Camos, 2009; Plancher & Barrouillet, 2013), also states that components' activation decreases once attention is elsewhere. However, this model also postulates the existence of two attentional processes that operate in working memory: the first one to process what is contained within the focus and the second to maintain the activation levels of previously attended components. Because of the limitations of the system, only one process can take place at a time. While one is facing an interruption, attentional focus would switch back and forth between the two tasks, that is, from processing the interruption task itself to refreshing the activation of the primary task. In other words, maintenance processes should depend heavily on the attentional switching. Therefore, a strong hypothesis would be that, when an interruption task does not allow maintenance, activation of components related to the primary task should decay within 30 s. On resumption, the RL would be longer than after an interruption that allowed maintenance because the schemata would have to be completely reactivated. Such working memory processes should be addressed by future models because they could become the basis of new strategies to reduce the effects of interruptions.

Existing Model of Interruption

Many authors focus mainly on the successful recovery after an interruption, that is, the shortest RL or lowest omission rate (Altmann & Trafton, 2007; Monk, Boehm-Davis, & Trafton, 2004). To support these researches, Altmann and Trafton (2002) have proposed the memory for goal (MFG) model, which describes the processes of encoding and resuming suspended goals and provides several recommendations. As noted earlier, the goals related to the primary task are suspended and the user is forced to encode them before performing the interruption task, a stage described as goal encoding. They will be retrieved in order to return to the primary task, a stage called activation. The highest activated goal will be the first one retrieved. Any goal could be either global (e.g., conducting a project) or specific (e.g., making a phone call), and every action would be governed by specific goals encapsulated in more global goals, creating a hierarchy (Cooper & Shallice, 2000). However, the authors do not tell us how different levels of the goal hierarchy would influence differentially the activation stage. Would it be easier to reactivate a very specific goal compared with a global one? Moreover, this model does not say much in case of conflicting goals between different levels of the hierarchy or in the case of resuming several goals at the same time, as during interrupted dual tasks. Would the specific or more global be recalled first, or would we observe a hierarchical pattern? The results of empirical researches would benefit designers and researchers in human–computer interaction.

During routine tasks, each step of action is governed by a control code. At every stage, this code monitors the current action to deduce what action should follow. Then, when an interrupted routine task is resumed, the highest activation would be used to regain its place in the procedure, resulting sometimes in errors in case of incorrect activations (Trafton et al., 2011). As shown by several authors, this retrieving can be altered because of interference with other goals present in working memory (Hodgetts & Jones, 2006; Morgan et al., 2013). Therefore, the MFG model postulated that inserting a brief delay before an interruption—also called an interruption lag—would help strengthen the correct activation, facilitating resumption.

The MFG model also generates hypotheses about the most appropriate timing of interruption, that is, when its occurrence is the least damaging for the primary task (Monk et al., 2004). Being interrupted at the beginning of a task might be less detrimental because this would generate less information to recall on resumption than when interrupted in the middle or the end of the primary task. In the two last cases, resumption should reactivate both the goals and the memory of what has already been completed and the next target to process (Adamczyk & Bailey, 2004).

Finally, this model also describes the resumption process in more detail, with an emphasis on the goals' reactivation. The activation stage is influenced by two factors: the history of recent retrievals (i.e., the more often it was retrieved, the easier the reactivation; Monk et al., 2004) and the relationship between the goal and the current set of mental or environmental cues (i.e., the more powerful the cues, the easier the reactivation; Morgan et al., 2013). Indeed, studies have shown that reinforcing the spatial location of the last processed item of the interrupted task improved resumption (Ratwani et al., 2007; Smith, Clegg, Heggestad, & Hopp-Levine, 2009).

Current Unsolved Issues About Factors Influencing Interruptions

Although many useful contributions have been made to elucidate and reduce the impact of interruptions for research and practical use (Altmann & Trafton, 2002; Boehm-Davis & Remington, 2009; McFarlane & Latorella, 2002; Morgan et al., 2013; Shallice, 2002; Shallice & Burgess, 1996; Trafton et al., 2011; Wickens & Gutzwiller, 2015; Zhang et al., 2004), many issues remain unanswered by the current theories and models, especially the MFG model (Altmann & Trafton, 2002). Hereafter, we will explore each of them, and questions that remain open for future investigations will be discussed.

TASK COMPLEXITY.

Task complexity has been found to influence cognitive processes and predict human performance in many experiments, including interruption paradigms (Cades et al., 2007; Mansi & Levy, 2013). Liu and Li (2012) defined task complexity as an "aggregation of any intrinsic task characteristic that influences the performance of a task" (p. 559). It is thus the collection of all possible components that can be grouped into several dimensions: size (number of components), variety (diversity in the numbers of task components), ambiguity (degree of unclear, incomplete or nonspecific task components), variability (changes or unstable characteristics of task components), temporal demands (time pressure or other time-related constraints), and so on. Although these dimensions are useful to study the impact of task complexity in one experimental paradigm, comparing different paradigms might be difficult because task complexity remains hard to quantify. Increasing task complexity is thought to generate a rise in the attentional resources invested to complete the task (Wickens, 2008). However, results sometimes show inconsistencies between experiments. This suggests that task complexity may affect performance differently when it concerns the primary task or the interruption task, or that task difficulty could have different effects depending on intrinsic dimensions of the paradigm used (e.g., the nature of the task, number of cognitive processes needed, or participants' training) or that task difficulty was in fact not well controlled because this variable is hard to operationalize. Researchers have manipulated either the complexity of the primary task or the complexity of the interruption task and observed their effects on temporal measures.

COMPLEXITY OF THE PRIMARY TASK.

According to the MFG model, the initial encoding stage would take longer in the case of a complex primary task compared with a simpler one because more components would have to be remembered. However important for this model, this effect of encoding stage duration seemed difficult to observe when explicitly manipulated experimentally (Adamczyk & Bailey, 2004; Bailey, Konstan, & Carlis, 2001). Other authors suggested a different explanation based on task-switching studies. According to them, going from a complex task to another one would take longer because of interference and carryover effects of schemata activations (Allport, Styles, & Hsieh, 1994; Eyrolle & Cellier, 2000; Leroy, 2009; Mayr et al., 2014; Wylie & Allport, 2000). To this day, it is not clear whether such an effect, if clearly demonstrated, would be explained by encoding processes or task-switching interference.

Also, Adler and Benbunan-Fich (2013) suggested that self-interruptions should be more frequent in case of a more complex primary task because of their positive effects on creativity, especially when one is having difficulty solving problems (Beeftink et al., 2008; Dabbish et al., 2011). However, such positive effects are still in debate and should concern only self-interruption, because external interruptions could not predict accurately the best moment to make a switch.

COMPLEXITY OF THE INTERRUPTION.

Many interruption studies used paradigms with varying complexities of the interruption task and tested their effects on resumption (Cades et al., 2007; Gillie & Broadbent, 1989; Zijlstra, Roe, Leonora, & Krediet, 1999). Data are inconsistent, however, because some showed longer RL (Basoglu, Fuller, & Sweeney, 2009; Cades et al., 2007; Mansi & Levy, 2013), but others did not (Gillie & Broadbent, 1989; Zijlstra et al., 1999). Once again, attention and working memory might explain such inconsistencies. During the resumption lag, specific processes occur, such as the reactivation of goals proposed by the MFG model (Altmann & Trafton, 2002). However, this model does not explain how the complexity of the interruption might influence that resumption. It simply implies that interference might generate longer resumption times without making clear predictions.

Other models could help answering this question, especially working memory ones. According to recent studies, during an interruption attention might rapidly switch between two important functions of working memory: processing the interruption task and maintaining information related to the primary task (Barrouillet et al., 2009; Plancher & Barrouillet, 2013). If the interruption is complex, it may prevent the maintenance processes, resulting in degraded activation of the primary task schemata, thus longer resumption lags afterwards. Therefore, it would not be the complexity of the interruption itself that generates a decline in resumption but rather the maintenance processes that could not operate properly, which is a completely new way of considering this effect. Here, the Time-Based Resource-Sharing model (Barrouillet et al., 2009) seems particularly relevant to the context of interruptions because the user has the intention to resume the primary task (cf. the second criterion of our definition), which could be interpreted in terms of refreshing mechanisms operating during the interruption task. Such refinement of the model, if verified, allows several new predictions and could pave the way for new research. For example, several ways already exist to influence the maintenance processes, such as manipulating the cognitive load or the interstimulus interval. Promising results are already published in fundamental working memory and should be extended to the interruption studies (Camos & Portrat, 2015; Plancher & Barrouillet, 2013).

INTERRUPTION DURATION.

The duration of interruption is an important factor that influences resuming processes in terms of both speed and error generation (Altmann & Trafton, 2007). For instance, Hodgetts and Jones (2006) showed interruption duration effects in the Tower of London task but only when using interruptions as short as 3 s. However, these effects were not always confirmed (Cades, Werner, Boehm-Davis, & Arshad, 2010; Einstein, McDaniel, Williford, Pagan, & Dismukes, 2003; Gillie & Broadbent, 1989; Li et al., 2006; Monk et al., 2008). What could explain such discrepancies? Can a model account for all effects observed after interruptions that range from a few seconds to several minutes? The MFG model states only that the activation of goals progressively decays within working memory during the interruption. However, that effect proved difficult to observe and might be influenced by other factors. To try to solve that problem, working memory models can provide us with some temporal boundaries. They propose that, in the absence of refreshing mechanisms (Barrouillet et al., 2009), decline should be complete after the first 30 s of interruption (Barrouillet et al., 2009; Cowan, 2008), much longer than what was initially proposed in previous interruption studies (Altmann & Trafton, 2002; Monk et al., 2008). This new perspective implies new hypotheses. For instance, after a 30-s interruption, the time to resume would be shorter in case of a low cognitive load (i.e., allowing the maintenance mechanisms) than in case of high cognitive load. This hypothesis has not been tested directly but would certainly be rewarding. Such effects, if demonstrated, could become the basis of new strategies to hinder the effects of interruptions. Several authors have already reported promising results in that direction (Cades et al., 2007).

TIMING OF THE INTERRUPTION.

Detrimental effects of interruptions can also depend on the moment when they occur during the primary task (Adamczyk & Bailey, 2004; Bailey & Iqbal, 2008; Bergmann, Kiemeneij, Fernández, & Kessels, 2013; Boehm-Davis & Remington, 2009; Botvinick & Bylsma, 2005). According to Adamczyk and Bailey (2004), any task can be divided into global steps, each containing several substeps. Interruptions occurring between the global steps (coarse breakpoints) are thought to be less damaging than between or during substeps (fine breakpoints). Although the authors showed differential effects of timing on emotional states, they failed to do so on behavioral performance. However, another study showed that interruptions occurring during the fine breaking points had more impact on memory of the primary task than during coarse breaking points (Boltz, 1992). The completion of a task can also be operationalized related to the beginning, the middle, and the end of that task. The MFG model posits that an interruption occurring at the beginning of a task should have less impact than in the middle or at the end of a primary task because of the number of elements the users have to reactivate at resumption (Altmann & Trafton, 2002, 2007). However, no such differences between early and late interruptions have been reported (Ratwani et al., 2006).

Once again, other interpretations exist about the influence of such effects. According to researchers studying the control of action, the effects of timing should vary greatly if the primary task is well known or, on the contrary, novel or complex (Cooper & Shallice, 2000; Shallice, 2002). In the case of fully automated tasks, the literature of action slips provides explanations about the potential impact of interruptions, although data do not seem consistent (Reason, 1990). According to Botvinick and Bylsma (2005), interruptions occurring at the end of a routine task might be less detrimental than at the beginning or at the middle. They based that assumption on the fact that when the successive steps of a routine action are executed, the most activated schema is used to indicate what step should follow. Activation of the current schema naturally rises when it is approaching its completion to facilitate the progression through the different steps. For these authors, this effect could reduce the effects of interruptions because highly activated schemata would be easier to resume. However, such effects would be highly dependent on the task itself and how it could be segmented. For example, when participants do not know when a task is supposed to end (i.e., a continuous task), an interruption occurring halfway through should be as detrimental as one occurring at the end. In the case of novel or complex primary tasks, more complex linear executive processing would be take place, first implementing new action schemata and then monitoring for errors (Shallice & Burgess, 1996). Interrupting a novel task just at the beginning, during the implementation of new actions, could be more impactful than at the intermediate or later steps, mainly because of monitoring processes (Shallice, 2002; Shallice & Burgess, 1996). To summarize, during both an automated and a novel task, an interruption at the beginning would have the most deleterious effects. Also, an interruption at the end would be less damaging in both situations. However, different predictions concern interruptions occurring in the middle of a task: For an automated task, it would be more damaging (as during an early interruption), although in the case of a novel task, it would be less damaging (as during a late interruption). Unfortunately, to date no study has been conducted to confirm this hypothesis.

INTERRUPTION TRAINING: PRACTICE.

Practice effects, that is, faster and more accurate performance due to the repetition of trials, can occur during a number of behavioral tasks. Nonetheless, only few researchers have been interested in studying training effects of repeated interruptions. According to Petersen and Posner (2012), training can change the functioning of the attention networks. Can resuming an interruption be trained? Which cognitive processes would be the best targets for such training? Can training one specific type of interruption be generalized to other types? In fact, several studies have already suggested the existence of practice effects specific to interruptions and resumptions (Cades et al., 2006; Eyrolle & Cellier, 2000; Pereg, Shahar, & Meiran, 2013). The MFG model posits the existence of two stages: the encoding and activation phases

(Altmann & Trafton, 2002). Concerning the encoding phase, it has already been reported that introducing memory-based strategies before the interruption generally facilitates resumption (Hodgetts & Jones, 2006; Trafton et al., 2003). Can we train participants to use better memory-based strategy before moving toward the interruption? Can these strategies be automatized? There are promising results in that direction (Morgan et al., 2013; Oulasvirta & Saariluoma, 2006). Concerning the activation phase, that is, the reactivation of schemata and goals, the authors state that such stage is influenced by the history of past retrieval: The more frequent they are, the easier the resumption. Recent experiments suggested such effects (Pereg et al., 2013). However, the exact functioning of this influence remains unclear. Is the history of goal retrieval stored forever in the system, or does it decline with time?

Also, can the decision and encoding steps be trained too? As far as task-switching is concerned, Cades et al. (2006) showed that repeated switches decreased time-related costs independently of the practice effect. They suggested that specific processes of task switching could be trained in order to respond more quickly and accurately to repetitive interruptions. But are such effects generalized to all types of interruptions afterwards? Unfortunately, it has been shown that training does not benefit other untrained switches (Pereg et al., 2013). As for the explanation, processes occurring during task switching and interruptions may involve a retrieving component, that is, the reactivation of the task components. If the retrieval of a specific task set occurs frequently, the process would become more automatic and should result in shorter resumptions but only for this specific task set (Cooper & Shallice, 2000). If the same interruption task occurs often during the same primary task many times, it is thus theoretically possible that the switching processes might get trained, as suggested by Cades et al. (2007). But that decrease would never generalize to other events. Finally, because working memory components might be heavily involved during interruption, they also could be the target of studies about practice and training effects. In fact, working memory and updating training are quite popular, even though their efficacy and generalizability have been questioned (Yin, Lee, Cheam, Poon, & Koh, 2015). Future studies should be focused on training programs targeting the maintenance components.

SIMILARITY.

The similarity between the primary task and the interruption task seems to play an important role in the generation of errors (Lu et al., 2013; Wickens & Gutzwiller, 2015). According to Wickens's model (2008), attentional resources derive from multiple energetic pools depending on the modality, sensory input, and output of the task or the stage of processing. This model makes numerous useful predictions about the impact of similarity. For instance, an interruption would be more impactful if its modality is the same as that of the primary task (Czerwinski, Chrisman, & Schumacher, 1991; Lu et al., 2013). This factor can be manipulated by varying the modality of stimuli presentation (e.g., visual, auditory, tactile), the schemata of the two tasks (i.e., they could both require the same mental operations on different stimuli), or the input and output channels of both tasks (e.g., one task could be visual and the other auditory but both could require a manual answer). It has been shown that interruptions that were similar to the primary task in terms of both modality and task schemata were more impactful than dissimilar ones (Czerwinski et al., 1991). Yet these results do not seem always replicable (Cades et al., 2010; Eyrolle & Cellier, 2000). Lu et al. (2013) compiled three meta-analyses to explore the similarity effects using the modality of the tasks. During an ongoing visual–manual primary task, tactile and auditory interruptions were far less impactful than visual ones. Such results point to promising ways to mitigate the effects of interruptions.

The DETOUR Framework

As discussed earlier, the biggest challenge interruption researchers are facing today is the multiplicity of disciplines that focus on such a complicated topic. As a consequence, the whole domain still struggles with interdisciplinary inaccuracies, such as confusing different phenomena such as interruption, distraction, and dual-tasking; mixing different cognitive processes, such as the effects of task-switching interference, control of action, and encoding; and overlooking research in fundamental domains such as recent working memory models. Facing this situation, we propose a research framework that describes the different stages involved when users face interruptions and clarifies the cognitive processes at play. Such a framework could push toward a better understanding of the past research findings and make it a coherent piece. This work could affect the research agenda of future studies and put the focus of research on the main factors and their interactions. Ultimately, the goal would be to create a cognitive model that can incorporate all aspects of interruptions.

Even though several models of interruption have already been proposed (Altmann & Trafton, 2002; Boehm-Davis & Remington, 2009; Trafton et al., 2011; Zhang et al., 2004), to our knowledge none have focused on cognitive processes recognized to affect interruptions such as decision making, attention (orientation, task switching, sustained attention, and executive control of action schemata), working memory, or goal encoding and retrieval altogether. Therefore, there is a need for a more integrative approach for a better understanding of such situations. We propose a new research framework named DETOUR (Decision–Encoding–Task Switching–Operating and Updating–Resumption; Figure 2) which incorporates in part some aspects of extant models (Altmann & Trafton, 2002) and several cognitive processes rarely associated with interruptions. It contains five stages, in part sequential and parallel, that can be specifically targeted for theoretical or practical purposes. We postulate that, after the first decision step is complete, all subsequent steps (encoding, task switching, operating and updating, and resumption) can be processed in cascade, that is, latter steps can begin operating before the total completion of preceding steps. This framework theorizes distinctions between different types of interruptions (immediate or delayed; McFarlane, 2002), distractions, and dual-tasking. It might also explain the overlap between distinct processes such as task switching and encoding.

Within this framework, we make several assumptions already demonstrated in the literature. First, executing an action requires the activation of the appropriate schemata (Monsell & Mizon, 2006;

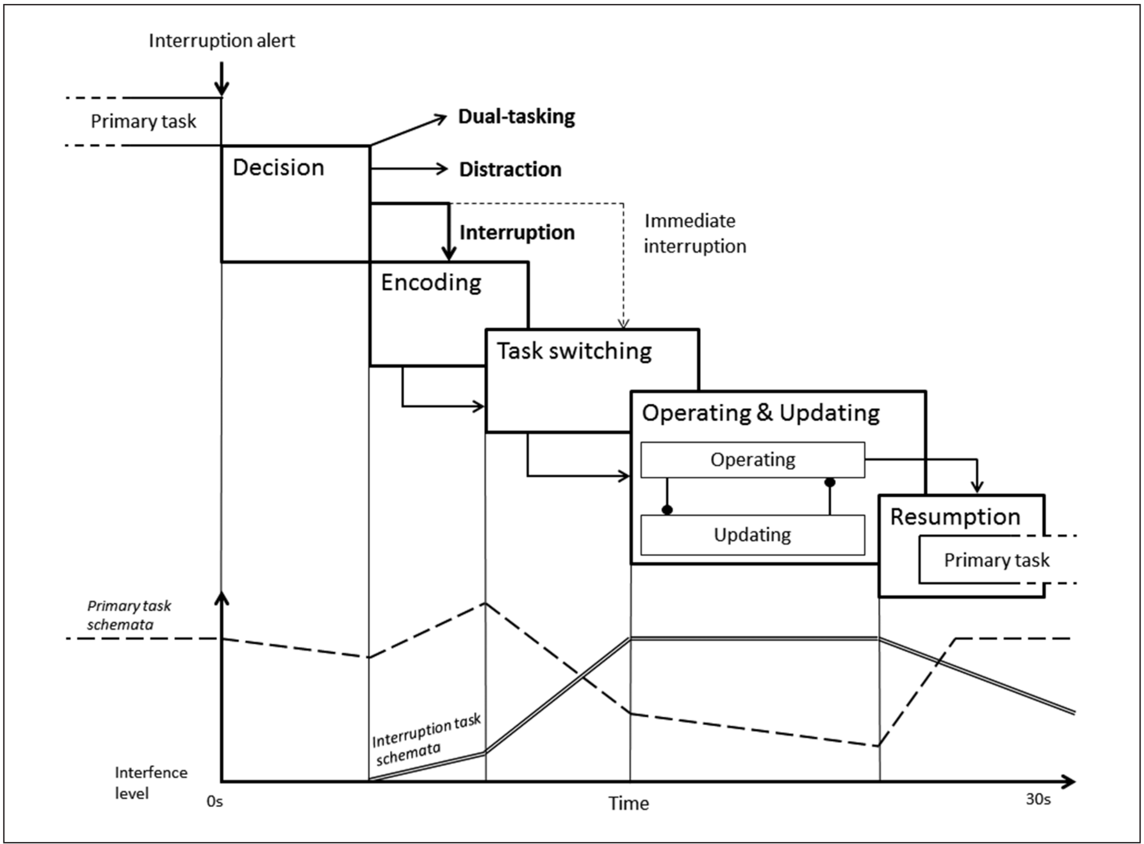

FIGURE 2. The DETOUR framework consists of five global steps after an interruption alert that influences the activation of the primary task schemata and goals, hence the general performance and resumption efficiency. In this example, the interruption lasts for less than 30 s, keeping the activation of primary task above the interference level. Each stage could become the center of future studies, even though it would be more rewarding to focus on every stage as a whole

Shallice, 2002; Vandierendonck et al., 2010) among those stored in memory and might generate continuous interference. Second, in order to select the appropriate schemata, supervisory mechanisms activate them, maintain them active during the execution of the task and monitor performance while inhibiting less appropriate schemata (Cooper & Shallice, 2000; Shallice, 2002). Third, the activation of the schemata related to the primary task decreases rapidly until complete extinction after 30 s (Altmann & Trafton, 2002; Cowan, 2008; Eyrolle & Cellier, 2000). This happens when switching to another task and in the absence of memory or maintenance processes.

Hereafter, we will briefly discuss each step of the DETOUR presented in Figure 2.

The decision stage comprises the initial disengagement from the primary task caused by an external or internal alert and the decision of what to do next: either performing both task concurrently (i.e., dual-tasking), immediately resuming the primary task (i.e., a distraction), or performing the interruption task (i.e., an interruption). Most importantly, because attention has been diverted, the primary task schemata should start decreasing during that stage. This particular step is rarely approached in interruption experiments because participants are always warned that they are about to be interrupted, and they can hardly ever decide to ignore the interruption tasks. Yet this specific stage might be the ideal target in aviation or medical domains to help reducing the impact of interruptions. For example, a promising recent computational model, the Strategic Task Overload Management (STOM), was proposed that could predict task choice and task switching during working memory overload (Wickens & Gutzwiller, 2015). According to the STOM model and other studies, such a rapid decision relies on components that weight the different outcomes of both situations by judging the "value of a task" (task priority and task interest). Crucially, this decision step might also be influenced by the moment of the interruption (Adler & Benbunan-Fich, 2013): An interruption alert occurring during coarse breakpoints (i.e., between global steps of the primary task; Adamczyk & Bailey, 2004) may result in deciding to perform the interruption more often than during fine breakpoints when participants are fully focused (Beeftink et al., 2008; Hodgetts & Jones, 2006). This hypothesis can be tested by manipulating the moment of the alert (during coarse vs. fine breakpoints) and letting participants decide when or whether they want to perform the interruption task. The number of decisions made toward interruptions or toward distractions for each condition could be one sensitive dependent variable for this stage. Because the choice would occur before executing the interruption task or returning to the primary task, the frequency of decisions should reflect how the first stage works. Different variables might influence this stage: the complexity of the tasks, the expectancy attributes, the level of urgency or threat (Bach, Hurlemann, & Dolan, 2015; Zhang et al., 2004), the relevance of the potential interruption (Shelton, Elliott, Lynn, & Exner, 2009; Zanto & Rissman, 2015), the engagement on the primary task (Robinson et al., 2012), and, if available, experiences of past decisions (MacLean & Giesbrecht, 2015; Zeigenfuse, Pleskac, & Liu, 2014). Moreover, the decision criteria might differ between participants, especially among patients with abnormal frontal functions such as attention deficit hyperactivity disorder (Bramham et al., 2012; Prehn-Kristensen et al., 2011) and frontal lobe damage (Law et al., 2004).

Then, the encoding stage allows the user to encode the task sets and goals for later resumption. The goals, action schemata, and memory of what has already been done are stored in working memory (Altmann & Trafton, 2002; Barrouillet et al., 2009; Bayliss, Bogdanovs, & Jarrold, 2015). Inserting a lag between the decision and the beginning of the interruption task usually allows a memory-based strategy, that is, a brief disengagement of attention from the alert to the primary task in order to encode as many components as possible for later resumption (Altmann et al., 2014; Morgan et al., 2013). This strategy reinforces the activation of schemata. On the contrary, an immediate interruption bypasses this stage, generally resulting in a faster decay and larger impacts on performance. These effects have already been the focus of many experimental and computational studies, as the main focus of the MFG model (Altmann & Trafton, 2002). Moreover, studies in prospective memory, which is the ability to form a representation of future actions, could concern this stage because participants might be also encoding the intention to return to the primary task. Studies have shown that intention can be encoded related to either a certain time or a certain event at which they should resume a task. Therefore, event-dependent prospective memory–based research might bring up new strategies to counter the negative impacts of interruption by providing efficient cues after the event that was associated primarily with the intention (Kretschmer-Trendowicz & Altgassen, 2016). Also, in parallel, preparatory mechanisms are in charge of activating the interruption-related schemata, as suggested in cued task-switching paradigms (Shi et al., 2014).

Later, the task switching step consists in the inhibition of the primary task schemata and activation of the interruption schemata to resolve potential interference (Monsell & Mizon, 2006; Sohn & Anderson, 2003). The higher the overlap between schemata, the larger the interference, hence the potential negative impacts on general performance such as action errors and decrease in speed (Lu et al., 2013; Wickens & Gutzwiller, 2015; Wylie & Allport, 2000). This hypothesis could be tested through the degree of similarity between the primary and the interruption tasks. For instance, during a visual primary task, two different interruption tasks differing only in terms of input modality (visual vs. auditory) could be used. Performance would be expected to drop as a function of increasing similarity between the tasks because higher overlap of components increases the interference and the frequency of errors (Reason, 1990; Wickens, 2008). Because of the user's intention to return to the primary task, interruptions differ from those of task-switching experiments, meaning that interruption-related interference might need more inhibition than task switching. Also, practice effects have been hypothesized (Cades et al., 2006; Eyrolle & Cellier, 2000; Petersen & Posner, 2012), but such training can be specific only to the switching between both tasks and does not generalize to others (Pereg et al., 2013). Also, this practice effect might disappear over time (Yin et al., 2015).

Afterwards, the operating and updating step contains the execution of the interruption task per se and the maintenance of components of the primary task (Barrouillet et al., 2009; Bayliss et al., 2015; Camos & Portrat, 2015; Plancher & Barrouillet, 2013). These two processes are mutually exclusive because they both require the focus of attention. The updating process could slow down the decline of schemata activation, potentially preserving it for longer than 30 s. The existence of maintenance processes has rarely been suggested and never directly studied in the interruption literature. Yet promoting them could become a new tactic for diminishing their impact, especially the computer-based ones. The updating component could be easily assessed by manipulating well-known variables such as the existence of an IAI, the duration or the cognitive load of the interruption. All these variables interfere with either the time dedicated to maintenance or the resources allocated for it. For instance, an experiment could consist in presenting two types of interruptions, one with long interstimulus intervals, allowing refreshing mechanisms to perform, and one with short intervals. The interruption with short intervals should be far more detrimental because activation of the components of the primary task would decay faster. Therefore, the TOT and the RL should be longer in this condition. It seems that there is a functional dissociation between early and later stages of working memory maintenance (Bergmann et al., 2013), leading us to believe that preventing early maintenance processes would be far more detrimental than later ones. Future studies about interruptions mediated by technologies should thus focus on allowing such early maintenance processes to hinder the impact of long interruptions.

Finally, during the resumption step, both task-switching and memory processes are involved at the same time to resume the primary task. First, the components of the primary task are reactivated while the components of the interruption are inhibited, also generating potential interference. However, this stage is more strongly characterized by the necessary reactivation of schemata, goals, and the memory of what has already been done (Altmann & Trafton, 2002; Boehm-Davis & Remington, 2009). If the activation of components had decreased below the interference level (in the case of an interruption lasting more than 30 s and preventing maintenance processes), a total reactivation would have to occur. One way to estimate the level of residual activation and the efficiency of the resumption stage would be to compare the time participants took when they initiated the primary task for the first time (initiation time, IT) and the RL. If the RL is shorter than the IT, it could mean some residual activation was used to restart the primary task faster. On the contrary, if the RL is equal or longer than the IT, it could mean that all traces of activation were gone and that participants had to reactivate them anew. It has already been demonstrated that external cues can facilitate resumption (Brudzinski et al., 2007; Ratwani et al., 2007); therefore, comparing RL and IT should be more relevant in the absence of such help. In that case, the two measures could be compared directly because they involve very similar processes, especially the activation or the reactivation of appropriate task schemata and goals (Shallice, 2002). Specific interruption-induced errors are often explained by failures in resumption processes (Cades et al., 2007; Reason, 1990; Trafton et al., 2011). This step has also been heavily studied. For example, it has already been demonstrated that environmental and contextual cues can help resumption by orienting toward the correct target within the primary task (Morgan et al., 2013; Ratwani et al., 2007; Smith et al., 2009).

We recommend measuring different variables when conducting interruption studies, mainly the task completion times, accuracy, and number and frequency of switching decisions. We believe that they all reflect different processes. Among the task completion variables, the TOT corresponds to the total time spent on the primary task, excluding the time spent on the interruption. This variable is not specific to a stage in particular and, in the interrupted condition, represents the cumulative effects of all stages. Therefore, most researchers use it only to compare uninterrupted trials with interrupted ones to show the general effects of interruptions. However, it is still possible to use the TOT to compare interrupted conditions when they differ only regarding one stage. For instance, it can be used to compare two immediate forced interruptions of the same duration but with different cognitive loads because only the updating component would differ between them. This would allow assessing directly the effect of isolated components or processes. The IAI can also be used as a measure of completion time of the primary task and has proved sensitive to interruptions (Ratwani et al., 2006). When using the DETOUR, three more specific variables can be used. First is the interruption lag (IL), which corresponds to the time participants take between the interruption alert and the beginning of the interruption task. This measure includes several steps of the DETOUR: decision, encoding, and task switching. Then, the time on interruption (TOI) can be measured or manipulated to specifically target the operating and updating components. For instance, manipulating the interstimulus interval during the interruption task should influence more the updating than the operating components. Finally, the RL corresponds to the time participants take to resume the main task and appears to specifically target the resumption stage (Trafton et al., 2003). Moreover, we suggest that these three variables should be interdependent because they all rely on the activation of components in short-term memory. The duration of the IL should greatly influence the duration of the RL, and this relationship should be mediated by the TOI. The distinction between all three variables and how they interact with each other could be tested with specific statistical tests, such as using two of them as covariant and analyzing the third variable.

In conclusion, the key principles of the framework can be summed up in five points: Interruptions activate five subsequent stages (decision, encoding, task switching, operating and updating, resumption); the longer the encoding, the more efficient the resumption processes; resumption efficiency depends in part on the level of residual activation remaining that follows interruption and interference; if the interruption lasts longer than 30 s, the primary task schemata will not be sufficiently active within working memory; and during the interruption, specific processes such as updating can maintain the primary task schemata for longer than 30 s. It is our belief that the DETOUR framework could help refining how researchers from different domains, either more fundamental or more applied, consider the different chains of events that might be generated by interruptions. We hope it will help build a stronger basis for future studies by reaffirming the conceptual differences between different types of interruptions, distraction and dual-tasking, and the respective contributions of attention and working memory models.

General Conclusion

In summary, this article proposes an updated review of the different effects of interruptions with the addition of the cognitive processes that could play a role. We also advocate for an operationalized definition of an interruption with four specific criteria. Furthermore, we discuss the main factors that influence interruption-related processes and that still challenge current models. Questions that remain open for future investigations are discussed. We also propose a research framework, the DETOUR, that may help in designing fundamental and applied experimental studies. Future research should take into account all the aforementioned points, try to respond to all remaining challenges, and try to consider all interactions between different factors to create a global model of interruptions.

NOTES

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