Background Sound Impairs Interruption Recovery in Dynamic Task Situations: Procedural Conflict?

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Abstract

Interruptions impair performance even on simple, static, laboratory-based tasks, but little research has looked at their impact in more complex and realistic settings that involve dynamically evolving circumstances and other environmental stressors. Using a radar operator task with or without background sound, participants were unexpectedly interrupted to complete another task which masked the radar screen as the scenario continually evolved. Task efficiency was impaired by interruption: Decision-making time was slower immediately following interruption, this cost being greater and persevering for longer in the presence of auditory distraction. Resumption time was also increased with distraction. Eye fixation durations were shorter following interruption, reflecting participants' attempts to rapidly re-encode and update their model of the situation. These results suggest that those processes involved in task resumption are also susceptible to background sound, and indicate a need for theories of task interruption to better specify the role of attention in interruption recovery.

Keywords: task interruption; dynamic displays; auditory distraction; command and control; eye movement; microworld.

System operators in critical command and control (C2) environments such as air traffic control, emergency services, and crisis management, must constantly monitor, assess, and integrate incoming information in order to make optimal decisions in dangerous, complex, and unpredictable task environments. The demand to support cognitive aspects of performance and decision making in such high-reliability environments is growing rapidly, but it is first necessary to gain a conceptual understanding of the cognitive limitations of the human operator to inform the development of such technological support tools. Task interruption is one particular constraint with which operators are often faced. Although there has been much recent progress in the study of interruptions, research has tended to focus on static tasks whereby participants return to the same, unchanged pre-interruption state (e.g., Hodgetts & Jones, 2006a, b; Monk, Trafton, & Boehm-Davis, 2008; Morgan, Patrick, Waldron, King, & Patrick, 2009); in the real world, however – particularly in dynamic C2 environments – circumstances generally continue to evolve throughout the interruption, rendering it more difficult to resume the task in hand. In the current work we use an actively-evolving, maritime risk management microworld task (synthetic environment) to assess both individual effects of interruption on dynamic decision making, and those in combination with auditory distraction. It is important to first gain a better understanding of the mechanisms operating during task interruption in complex dynamic tasks at a conceptual level, before it is possible to take practical steps to counteract any loss of efficiency in C2 work contexts.

Situation Awareness and Interruption of Dynamic Tasks

The interruption literature using dynamic task environments is limited (e.g., Hunter & Parush, 2010; St. John & Smallman, 2008; Tremblay, Vachon, Lafond, & Kramer, 2012), but disruption to performance is likely to be even greater than that already demonstrated in static tasks if a higher workload is incurred (Stone, Dismukes, & Remington, 2001). In typical C2 situations, operators must manage several tasks and deal with continuously evolving circumstances; for example, an operator might be interrupted by a request from the operation room supervisor, or simply by a temporary ‘freeze’ of the visual display device that he/she is monitoring. Resuming the task involves regaining situation awareness (SA); that is, perceiving elements in the environment, comprehending their meaning, and being able to project their status in the near future (Endsley, 1988). Unlike static tasks, when all elements are as they were prior to interruption, regaining SA in C2 situations requires a more thorough reassessment of the situation when the task resumes in order to assimilate the mismatch between pre- and post-interruption scenes (St. John & Smallman, 2008; Tremblay et al., 2012). Clearly, an ability to extrapolate forward in time—an ability referred to as the third and highest level of SA (Level 3) by Endsley (1995)—and to predict how elements of a situation may have evolved will aid this reacquisition process. Recent work suggests that to some extent, participants are able to project along the same speed/trajectory of tracked objects to recover their new location following an unexpected break in a multiple object tracking task (Hunter & Parush, 2010). However, the finding that accuracy was lower for moving objects than for those which remained in their same pre-interruption position illustrates the higher workload incurred by dynamic tasks, a factor that may be underestimated in many static tests of interruption. As well as updating a mental model of the location/status of items on the screen, operators in continually evolving environments must also detect any important incidents or changes that may have taken place during an interruption (e.g., St John & Smallman, 2008). Undoubtedly task interruption presents a challenge for maintaining SA in C2 settings, and the extent of this disruption may be moderated by other stressors present in the C2 environment.

Auditory Distraction

C2 situations prone to interruptions are often also subject to background sound, a feature of the work environment that is known to impair performance on a range of cognitive tasks (i.e., the irrelevant sound effect; for reviews, see Banbury, Macken, Tremblay, & Jones, 2001; Beaman, 2005). Studying the combined effects of auditory distraction and task interruption will not only have key applied implications, but will also speak to the role of attention in interruption recovery which is not well addressed by main theoretical accounts of task interruption. Previous conceptual work on interruptions has been successful in investigating such issues as interruption duration (e.g., Hodgetts & Jones, 2006b; Monk et al., 2008), complexity (e.g., Hodgetts & Jones, 2006b; Monk et al., 2008), and modality (Ratwani & Trafton, 2010), as well as characteristics of the primary task such as task demands (e.g., Monk, Boehm-Davis, & Trafton, 2004) or the availability of cues (e.g., Hodgetts & Jones, 2006a, Ratwani & Trafton, 2008, 2010). In the current work we examine whether features other than those associated with the primary and secondary tasks – i.e., elements of the external task environment – may exacerbate the impact that an interruption can have. The quiet conditions under which laboratory research is typically conducted may underestimate the effect of task interruption in real-world settings, but in the current work we take into account both isolated and combined effects of interruption that could occur in a typical, complex C2 environment (cf. Lafond, Vachon, Rousseau, & Tremblay, 2010).

One mechanism proposed to account for the effects of background sound is attentional capture, whereby the extraneous sound attracts attention away from the concurrent task (e.g., Banbury et al., 2001; Chein & Fiez, 2010; Cowan, 1995; Elliott, 2002; Hughes, Vachon, & Jones, 2005, 2007; Näätänen, 1990; Parmentier, 2008; Schröger, 1996; Vachon, Hughes, & Jones, 2012). A large body of evidence suggests that performing mental activities in noisy environments—whether it is speech or non-speech sound—is less than optimal, since sound is processed in an obligatory fashion: humans cannot shut or divert their ears in as ready a manner as they can shut or divert their eyes (see Hughes & Jones, 2003). Although the effects of irrelevant sound have been studied mainly using artificial auditory simulations, such as sequences of discrete speech items or tones (see Jones, 1999), cognitive performance is also vulnerable to more realistic auditory simulations such as low-priority auditory warnings (e.g., Banbury, Fricker, Tremblay, & Emery, 2003), irrelevant radio messages (e.g., Banbury, Jones, & Emery, 1999; Hodgetts et al., 2005; Tremblay, Parmentier, Hodgetts, Hughes, & Jones, 2012), and office noise (e.g., Banbury & Berry, 1997, 1998; Perham & Banbury, 2012). Background sound is most likely to capture attention if it contains unexpected changes (e.g., Parmentier, Elsley, Andrés, & Barceló, 2011; Vachon et al., 2012), for example, an unpredictable change in voice (e.g., Hughes et al., 2007) or temporal rhythm (e.g., Hughes et al., 2005). In C2 situations that often rely on cooperative teamwork and multiple sources of incoming information, speech may often be fragmented with unpredictable onset, which is also likely to be particularly distracting (Emberson, Lupyan, Goldstein, & Spivey, 2010). In terms of interruption, we may expect that anything diverting participants' attention away from the task in hand when trying to regain SA would have a detrimental effect, as this would leave fewer attentional resources available for the demanding job of recovering primary task goals and reinstating task context.

Theoretical Framework

One popular framework used to understand interruption effects is Memory for Goals (MFG; Altmann & Trafton, 2002). Derived from the ACT-R (Adaptive Control of Thought – Rational) cognitive architecture (e.g., Anderson & Lebiere, 1998), it models the suspension and resumption of goals in a problem solving task, but can also be applied more widely to the suspension and resumption of task goals during an interruption. The model is based on the idea that all memory elements have a level of activation that is subject to noise and fluctuates around a mean value. When central cognition queries memory, it is the most active element at that particular moment – the one which exceeds the activation threshold—which is returned. The activation of episodic memory codes is subject to decay over time, but activation can be boosted through strengthening (e.g., rehearsal), or priming (e.g., associative cues present in the environment both when the task is suspended and when it is to be resumed). The model highlights the typical time course of an interruption, emphasizing the importance of a pre-interruption preparatory period (the 'interruption lag')—which can be used for rehearsal of the current state or encoding of contextual cues—and the post-interruption phase (the 'resumption lag')—during which priming can aid SA recovery and reinstating previous task goals. We might expect the cognitive system to be particularly vulnerable to errors at critical points around an interruption, and especially in the presence of auditory distraction which may lead to inadequate encoding of situational cues and/or errors in goal retrieval.

One issue on which the MFG model is not well specified is the role of attention, and it is unclear whether the processes of strengthening and priming are relatively automatic or more resource-demanding. If one assumes that they are effortful, and background sound diverts attentional resources away from these processes—especially at key points immediately before and immediately after interruption—then the cost of interruption should be greater than without distraction, due to a compromising of the strengthening/priming processes. However, Altmann and Trafton (2002) suggest that the forging of associative links between a to-be-suspended goal and the task environment may occur relatively automatically simply by co-occurrence; if so, then perhaps background sound should not impact further upon interruption effects, and rather any variation in the degree of disruption would be determined solely by factors relating to the primary and secondary tasks themselves.

Unlike MFGs which is a single channel model, Multiple Resource Theory (Wickens, 2002) proposes that attention can be more successfully divided between tasks if they each tap into separate pools of attentional resources (e.g., visual vs. auditory, spatial vs. verbal). According to this framework, one might therefore expect disruption if a visuo-spatial radar task was interrupted by another visual task, but would not expect background sound to adversely affect primary task performance since resources can be divided in an optimal manner.

Another theory of multi-task performance that might speak to the current issues is that of threaded cognition (Salvucci & Taaatgen, 2008), whereby 'threads' represent streams of thought associated with a particular task and the execution of which is coordinated by a serial cognitive processor. Multiple threads can be active concurrently and executed in parallel, but bottlenecks occur if two threads call upon the same peripheral resource (cognitive, perceptual, motor) or demand attention from the central procedural resource at the same time. Threaded cognition can account for a range of multitasking phenomena, and has been reconciled with the MFG theory in the way that separate task threads are interleaved to manage the rehearsal and retrieval processes operating during interruption (Salvucci, Taatgen, & Borst, 2009). Concurrent background sound would presumably add an additional task thread, but would not be expected to interfere with a visual task since it draws upon auditory processes.

Eye movements and Interruption Processes

Eye tracking can capture processes in both static and dynamic tasks in an unobtrusive way (e.g., Lafond et al., 2009; Poole & Ball, 2006), and provides an innovative way to understand cognition in applied settings. Eye movement analyses have been used to provide insight into the associative priming process of MFG: Using a static data entry task, one study showed that participants' gaze returned quite accurately to the pre-interruption task area where associative cues could help to boost activation of the interrupted task goal (e.g., Ratwani & Trafton, 2008; 2010). However, although spatial memory may help guide task resumption in static tasks, it is not clear how the MFG priming process would play out if the scene that participants return to after interruption is not the same as that left at the onset of the secondary task. Returning to the same place would not necessarily generate useful resumption cues, and a better strategy would be to seek out the projected position of objects in accordance with their movement during the interruption. Within a dynamic supervisory control task, an analysis of eye movements was able to distinguish between different behaviors when comparing between interrupted and non-interrupted tasks (Gartenberg, McCurry, & Trafton, 2011). Following interruption, SA was reacquired by scanning numerous previously fixated objects (to reinstate earlier goals/planned actions through priming), but when there was no task break, participants fixated on fewer and novel objects (seeking new events). Although these data do not indicate whether participants' gaze first returned to the previously fixated object's pre-interruption position or to the newly located object itself (to show some awareness of movement during the interruption), it suggests that the process of seeking out previous objects is a necessary strategy to help regain SA and reinstate previous task context through associative cues. Such a process may be more attention-demanding and time consuming in dynamic rather than static tasks due to environmental changes. According to MFG, previous goal representations can be reinstated through external (fixation) cues or internal (memory, imagination) cues which increase activation of the suspended goal state. In dynamic situations, one could assume that internal cues are particularly important as external pre-interruption cues could be less reliable.

The Current Study

The MFG model's general principles of activation, decay, and contextual cues have proven useful, but further work is needed to determine the extent to which they apply to dynamic tasks and the extent to which attentional factors may impact upon these processes. In the current experiment we co-varied the presence/absence of task interruption and irrelevant sound in a within-subject manner, to assess the individual and combined effects of interruption and background sound in a complex and dynamic microworld task. Experimental settings have their limitations (Dismukes, 2010), but microworlds (or functional simulations/synthetic environments) simulate the essential features of a dynamic system within a controlled environment and provide the optimal compromise between external realism and empirical control (Gray, 2002). The Simulated Combat Control System (S-CCS) microworld (Lafond et al., 2010; Vachon, Vallières, Jones, & Tremblay, 2012) is similar to the Argus Prime radar task (Scholles & Gray, 2000) and provides a simplified simulation of above-water C2 warfare practiced aboard the Canadian Navy's frigates. The participant plays the role of a tactical coordinator who must be sensitive to changes in the operational space, conduct aircraft threat assessments including categorization and prioritization of threats, and plan and schedule the operation of combat power. It does not require particular expertise, and provides an immersive yet controlled environment which bridges the gap between ecological validity and empirical precision.

In the present study, we collect behavioral performance measures (decision-making times and task-resumption times) and eye-movement data. The expectation is that decision-making times will not be affected across the entire scenario but rather will be localized to specific epochs after the interruption periods. We expect slower decision-making times immediately following interruption as participants need to gradually regain SA and reinstate previous task goals whilst making the aircraft classification decisions. MFGs makes no explicit predictions about whether this recovery process might be impeded by the additional presence of background sound, while Multiple Resource Theory and threaded cognition actively imply the absence of interference on a visual task from the auditory domain. Nevertheless, there remains the possibility that task-irrelevant sound could create a divided attention condition that reduces the availability of resources needed for interruption recovery, resulting in slower decision making.

Eye movements will be measured in an event-based manner, comparing periods immediately before and after the interruption in order to infer strategies and cognitive processes operating around these key points. Eye fixations, a widely accepted index of cognitive processing (e.g., Goldberg & Kotval, 1999), can nevertheless be interpreted in various ways depending on the context in which they are recorded (see, e.g., Poole & Ball, 2006). A greater number of fixations has been associated with the process of rapid encoding/updating of a visual scene (Gartenberg et al., 2011), a greater uncertainty in recognizing target information (Jacob & Karn, 2003), as well as representing a more difficult search as the participant expends more effort to take in all relevant information from the presented display (Goldberg & Kotval, 1999; Van Orden, Limbert, Makeig, & Jung, 2001). With regards to fixation duration, longer fixations have been associated with greater difficulty in extracting information (e.g., Goldberg & Kotval, 1999; Just & Carpenter, 1976) and an increase in cognitive processing loads (Callan, 1998; Recarte & Nunes, 2000), while shorter fixations might represent attempts to rapidly encode a visual display (Gartenberg et al., 2011). In line with Gartenberg et al.'s (2011) eye-movement analysis, we might expect more and shorter fixations following interruption as participants attempt to regain SA. In terms of background sound, this may have little or no effect on the visual radar task (e.g., Wickens, 2002), or, resisting auditory distraction may increase the effort needed to extract necessary information from the display, thus resulting in longer and fewer fixations. Again, the combined effects of interruption and background sound are uncertain, but it is possible that the process of rapidly seeking out retrieval cues may be slowed by distracting background speech.

Method

Participants

Twenty-one students at Université Laval (11 men; mean age = 22.6 years) participated in the two-hour experiment and received CAN $20 for their time. All were naive to the experimental hypotheses and all reported normal or corrected-to-normal vision and normal hearing.

Apparatus/Materials

The experiment used the S-CCS microworld (see Vachon et al., 2012) run on a PC computer. It provides a functional simulation of threat evaluation and combat power management processes (i.e., response planning, execution, and monitoring) that can also be generalized to other C2 situations. The visual interface comprises three parts; a black radar screen, a list of parameters relating to the aircraft selected, and a set of action buttons (see Figure 1). At the center of the screen is the ship with multiple aircraft moving in the vicinity in real time. An aircraft is represented by a white dot surrounded by a green square with a line attached; this line indicates the direction in which the aircraft is moving, and its length is proportional to the aircraft speed. Each scenario or ‘burst’ lasted four minutes and involved 27 aircraft in total, starting with five and increasing to a maximum of 10 at any one time. Sixteen different scenarios (four for each conditions) were created (e.g., different parameter values, different trajectories), but were equivalent in difficulty (e.g., number of aircraft, number of hostile aircraft).

A PowerPoint tutorial, which participants read through at their own pace, explained the context of the simulation and the tasks to execute. Their task was threefold: 1) to determine the threat level (hostile, non-hostile, uncertain) of all the aircraft on the radar screen; 2) determine the threat immediacy of hostile contacts (i.e. how long until they will hit the ship); and 3) engage a missile to neutralize a hostile contact. Clicking with the mouse on an aircraft icon would turn the surrounding square red and display five parameters relating to that aircraft in the parameters list: country of origin (*ADRK* = threatening), altitude (*low* = threatening), intention friend or foe (IFF; *foe* = threatening), weapons detected (*yes* = threatening), and military emissions (*yes* = threatening). Other parameters were also displayed that were not part of the threat assessment task (e.g., heading, distance, speed). Participants were to classify each contact as either non-hostile (0 or 1 threatening parameters), uncertain (2 or 3 parameters), or hostile (4 or 5 parameters), and click on the corresponding action button. None of the critical parameters was intrinsically more important than the others. Once an aircraft had been classified, the white dot changed color according to the threat level assigned to it: green (non-hostile), yellow (uncertain), or red (hostile). The status of objects could change over time according to updated intelligence, and so it was sometimes necessary to check back at the parameters of classified aircraft in order to re-assess threat level. There were eight hostile aircraft in each scenario that were programmed to hit the ship. For those contacts considered hostile, the participant had to further classify the threat immediacy (on a scale 1 to 3), based upon the TCPA parameter (Time to Closest Point of Approach; < 15 s, 15–30 s, or > 30 s, respectively). The participant could then choose to launch an anti-missile in defense, taking into account the probability of hitting and destroying the hostile aircraft (the radar screen was divided into hit-accuracy zones: 0%, 25%, 50%, 100% according to distance from the ship). Clicking on the ‘engage’ button launched a missile with a 2-second delay, and only one could be airborne at any one time.

A Tobii T1750 eye tracker (Tobii Technology, 2006) was used to monitor eye movements throughout the task, integrated into a 17-in monitor with a resolution of 1024 × 768 pixels and with a sampling rate of 50 Hz. Eye movements were calibrated after the microworld familiarization session, ensuring that the participant was seated approximately 50 cm from the eye-tracker computer screen. ClearView software (Tobii Technology, 2006) was used to analyze eye movement data.

Manipulations

A 2 (task interruption: present or absent) × 2 (auditory distraction: present or absent) repeated-measures design was used. On half of scenarios, the S-CCS system initiated interruptions between 55 s and 125 s into the 4-min burst. The interruption lasted 24 s, during which time the whole S-CCS interface went blank and was replaced by three consecutive questions on the task situation and mission status, which were intended to simulate requests for information from an external authority. Each question required clicking with the mouse to make a yes or no response, and changed automatically after 8 s. After presentation of all three questions, the S-CCS interface was restored. Participants were to resume that same scenario and reinstate primary task goals, bearing in mind that it would have continued to evolve in real time during the interruption. To avoid differences in task difficulty between the interruption and no-interruption conditions, we ensured that no aircraft would become hostile during the 20 s immediately preceding or following interruption.

Participants wore headphones throughout the experiment. For half of scenarios there was no background sound, but in the other half participants were played a 4-min recorded communication between two participants performing a different C2 simulation (a forest firefighting mission). The background sound was therefore realistic but irrelevant to the task in hand, and participants were told that it should be ignored. These auditory sequences were created using a 3-D auditory recording system and digitally edited so that conversations sounded fragmented in order to simulate telecommunication interference and increase the disruptive power of the irrelevant sound (see Emberson et al., 2010). Each participant completed all four experimental conditions, the order of which was counterbalanced in a partial Latin square design.

Measures

The microworld task gave rise to several dependent variables. *Decision-cycle* time reflected the time between selecting one aircraft and selecting the next: This incorporated parameter assessment and classification, possibly an immediacy assessment and weapon engagement (for hostile aircraft), and the time to search and select the next aircraft. It was analyzed in an event-based fashion with interruption as an anchor point, comparing decision-making times before and after the unexpected break in task. Another time-based measure was *resumption lag*, or the time it took the participant to make the first action after an interruption. Resumption lag is one of the measures typically taken to assess the impact of interruption (e.g., Hodgetts & Jones, 2006a, b; Trafton, Altmann, Brock, & Mintz, 2003) and may reflect the time necessary to reactivate suspended task goals and to regain SA (e.g., Gartenberg et al., 2011). Eye movements were recorded to assess differences in the number and duration of eye fixations in different sound conditions and in time periods before and after the interruption. The threshold to detect an eye fixation was set at 100 ms and the fixation field corresponded to a circle with a 30-

pixel radius. Participants were asked to rate mental load and time pressure after each burst by clicking at the appropriate number on a 10-point Likert scale where 1 = low, 10 = high (adapted from the NASA-TLX questionnaire; Hart & Staveland, 1988).

Procedure

Participants read through the PowerPoint tutorial which informed them of all aspects of the S-CCS microworld. To check understanding of all the instructions before the start of the experiment, participants were presented with nine static screenshots from the microworld task and asked to perform the threat classification task and the threat immediacy task, if applicable. They were then given a 1-min session of the simulation in order to familiarize themselves with the microworld environment. Two training sessions were then completed, followed by four test sessions after a 15-min break. Each session comprised four bursts of four min each which covered each of the four experimental conditions (control, interruption, distraction, interruption + distraction). A summary of instructions was presented on screen at the beginning of each session, and participants clicked a 'Continue' button to initiate the first burst. At the end of each burst, subjective workload was measured using the NASA-TLX technique (Hart & Staveland, 1988).

Results

Dependent variables were analysed by comparing performance during specific time periods before and after the interruption. As post-interruption recovery might be fairly quick, taking more global measures throughout the 4-min bursts might not be sensitive to interruption effects. The following analyses therefore took into account three critical time periods around the point of interruption (the 20 s before, the 20 s after, and the next 20 s after that). Effect sizes were estimated using Cohen's *f* for *F* tests and Cohen's *d* for *t* tests.

Decision-Cycle Time

Mean decision-cycle time was recorded for the three critical time periods (i.e., -20s, +20 s, +40 s around the interruption), for both quiet and background sound interruption trials (Figure 2). A 3 (time period) × 2 (distraction: present or absent) repeated-measures ANOVA revealed a significant main effect of time interval, $F(2, 40) = 26.84$, $MSE = 151721.75$, $f = 1.16$, $p < .01$, with each of the three 20-s intervals significantly different from each other (*p*s < .002); decision-cycle times were fastest before interruption and slowest during the 20 s immediately following interruption. There was a significant main effect of distraction, $F(1, 20) = 25.32$, $MSE = 136623.45$, $f = 1.13$, $p < .01$ with decision cycles significantly slower in the presence of auditory distraction. More importantly, the interaction between distraction and time interval was also significant, $F(2, 40) = 11.87$, $MSE = 177081.99$, $f = 0.77$, $p = .01$. The decomposition of this interaction with dependent-samples *t* tests showed that the presence of auditory distraction had no effect on decision times before interruption occurred, $t(20) < 1$, $d = 0.38$, but decision time was slowed to a greater extent at both 20 s, $t(20) = 2.16$, $d = 0.97$, $p = .043$, and 40 s after interruption, $t(20) = 5.87$, $d = 2.54$, $p < .001$, in conditions with background sound compared to scenarios without. Bonferroni multiple comparison tests revealed that with distraction, decision cycle time still remained significantly elevated 40 s after interruption compared to decision times before the interruption (*p*s < .001); however, in the no distraction condition, the increased decision times that were evident immediately following interruption (+20 s; $p = .001$) had returned to pre-interruption levels by the +40 s time interval ($p = .343$). Further analyses revealed that decision cycle time in the distraction condition had returned to baseline (i.e., pre-interruption) at + 60 s (M = 4363.98 ms; SD = 755.93; comparison with decision time at -20 s: t(20) < 1, p = .779, d = 0.06). We also examined decision cycle time for uninterrupted control conditions by measuring the time around where the interruption would have occurred (Figure 3), but there were no main effects and no interaction (all *F*s < 1, *f*s < 0.20).

Resumption lag was defined as the time between the offset of interruption and the first action (mouse click) on the main task. Generally, the first action participants made after an interruption was to select an aircraft (161 times out of 168 interruptions) rather than to make a classification. Resumption lags were significantly longer in the presence of auditory distraction (mean = 2149.55 ms, SE = 130.64) compared to without (mean = 1880.71 ms, SE = 129.21), $t(20) = 2.17$, $d = 0.97$, $p < .05$.

Eye Movements

Eye-tracking data were collected using the same three time intervals as above (Figure 4). More and shorter fixations have been associated with rapid encoding of a visual scene, while longer fixations have been associated with a more effortful search. Both mean fixation duration (in ms) and mean number of fixations were submitted to the same 3 (time interval) × 2 (sound condition) repeated-measures ANOVA. The main effect of time interval on fixation duration was significant, with shorter fixations following the occurrence of an interruption compared to before, $F(2, 40) = 11.30$, $MSE = 455.73$, $f = 0.75$, $p < .01$. A main effect of distraction showed that fixations were significantly longer in the presence of background sound, $F(1, 20) = 5.61$, $MSE = 221.43$, $f = 0.53$, $p < .05$, and the interaction between distraction and time interval was also significant, $F(2, 40) = 4.03$, $MSE = 224.89$, $f = 0.45$, $p < .05$. Simple effects tests showed that fixations were significantly longer in the presence of distraction only during the 20 s following interruption, $t(20) = 3.60$, $d = 1.61$, $p = .002$, but not significantly different at either –20 s ($p = .074$, $d = 0.84$) or +40 s ($p = .285$, $d = 0.49$). Bonferroni multiple comparison tests showed that in the no distraction condition, fixation duration was significantly shorter in the 20 s following interruption (p = .006), but had slowed to pre-interruption levels by 40 s post-interruption (p = .189). With distraction however, fixation duration was shorter than the pre-interruption level at both the 20 s (p < .001) and 40 s following interruption (p = .011). For uninterrupted control conditions (Figure 5), there were no significant differences in terms of fixation duration (Fs < 1.64, ps > .207, fs < 0.29).

Regarding the number of fixations, there was a main effect of time interval, $F(2, 40)$ = 19.37, MSE = 101.10, f = 0.99, p < .01, with each of the time intervals different from each other (ps < .05). The fewest fixations were made before interruption, and the most in the 20 s immediately following interruption. Distraction had no significant effect on the number of fixations, $F(1, 20)$ < 1, MSE = 127.38, p = .715, f = 0.09, and there was no interaction between time interval and distraction, $F(2, 40)$ < 1, MSE = 94.71, p = .915, f = 0.07. For uninterrupted control conditions, there was no significant effect of time interval around the corresponding point of interruption, and no interaction with distraction (Fs < 2.3, ps > .15, fs < 0.34).

A further point of interest was to see if first fixations following interruption focused on the pre-interruption location of a previously attended object (spatial memory for pre-interruption state), or the current location of an aircraft (projected position). ‘Anticipation’ of the new position of aircraft was very rare, and only 1.2% of the time did participants fixate on the most threatening aircraft both immediately before and immediately after the interruption. Most first fixations (63.7%) were in fact random, focusing on neither the old nor the new location of aircraft on the radar. In 22.1% of cases, the first post-interruption fixation was on the most threatening aircraft (generally the one closest to the ship) regardless of what was fixated just prior to interruption.

Performance Measures

Classification accuracy was assessed using the same 2 × 3 repeated-measures ANOVA as before (Figure 6), but there was no effect of interruption, either alone or in combination with distraction (*F*s < 1, *f*s < 0.16). Performance was also assessed in terms of the number of ship hits by a hostile aircraft. This was a rare occurrence, and was no more likely to occur on interrupted (M = 5.58%, SD = 2.91) than uninterrupted trials (M = 5.88%, SD = 2,36), $t(20) < 1$, $d = 0.08$.

Workload

Self-reports of perceived mental load and temporal pressure using the NASA-TLX scales were taken after each burst on a 10-point Likert scale (Figure 7). A 2 (interruption: with or without) × 2 (distraction: with or without) repeated-measures ANOVA showed higher reports of mental load under conditions of auditory distraction than in silence, $F(1, 20) = 10.26$, MSE = 0.30, $f = 0.72$, $p < .01$. There was however no effect of interruption $F(1, 20) = 2.56$, MSE = 0.12, $f = 0.36$, $p = .125$ and no interaction, $F(1, 20) = 2.20$, MSE = 0.11, $f = 0.72$, $p = .15$. Regarding temporal pressure, there was again a significant effect of distraction, $F(1, 20) = 4.22$, MSE = 0.22, $f = 0.46$, $p < .053$, and also one of interruption, $F(1, 20) = 8.35$, MSE = 0.17, $f = 0.65$, $p < .01$, such that background sound and task interruptions served to increase participant perceptions of temporal pressure. There was no interaction between the two factors ($F < 1$).

Discussion

The current experiment aimed to assess the effect of auditory distraction on dynamic task interruption, both of which are common occurrences in many C2 environments. Moreover, we aimed to use background sound as a way to understand more about the role of attention in interruption recovery, an aspect that is not clearly addressed by the MFG model. Results demonstrated the disruptive nature of interruptions to task performance, and that background sound can exacerbate this disruption. Decision-cycle time was significantly increased following an interruption; furthermore, this effect was even more marked in the presence of background sound, and participants took even longer to return to pre-interruption decision-making speed. Resumption time after interruption was also greater in the distraction condition. The prolonged effects of interruption in the presence of background sound were also supported by differences in eye movements between the two conditions. Such results indicate that features of the external environment can impact upon the degree of disruption caused by an interruption, and suggest an important role for attention in interruption recovery.

Eye-movement data were able to provide a useful compliment to the standard measures of decision-cycle and resumption times. There were more and shorter fixations immediately after the interruption than before, which is thought to reflect rapid updating of the newly evolved scene (e.g., Gartenberg et al., 2011) and a greater search effort (e.g., Van Orden et al., 2001) compared to before interruption or much later in the task. In quiet, fixation duration returned to pre-interruption levels sooner than when participants were distracted by extraneous sound. This suggests that regaining SA following interruption takes longer in the presence of distraction, perhaps because all attentional resources are not devoted solely to the task of interruption recovery. As such, this indicates that attention plays a crucial role in the task resumption process although this is not well understood in theoretical accounts of task interruption. Fixations were longer under conditions of distraction than no distraction – even in the immediate post-interruption period – perhaps indicating that participants needed to attend for longer and expend greater effort in order to glean the same information (e.g., Just & Carpenter, 1976). Eye-tracking data can reveal aspects of cognition in applied settings that may be missed by standard performance measures. For example, although resumption time provides a useful indication of time to reactivate primary task goals—and may be particularly applicable in static tasks—the current results show that the time course of recovery may actually be much longer (Altmann & Trafton, 2007), especially in the case of complex dynamic situations (Tremblay et al., 2012). The duration of eye fixations was still shorter in the distraction condition 40 s after interruption, showing that although participants had actively resumed performance on the task, recovery was still not complete and still required re-encoding and updating of the situation model in order to achieve pre-interruption levels of SA in this complex and dynamic task.

Although interruptions affected decision times they did not impair accuracy, a finding that is in keeping with previous interruption studies reporting increased latencies but no increase in error (e.g., Hodgetts & Jones, 2006a, 2006b; Monk et al, 2008; Trafton et al., 2003; although see Altmann, Trafton, & Hambrick, 2013). For classification accuracy, it may have been the case that participants took their time reconstructing mental context from the rich perceptual display, a strategy that lengthened decision making time but preserved accuracy. Self-reports indicated an increase in temporal pressure on interrupted scenarios but no greater mental load, while auditory distraction increased both these variables. Thus although interruption did not appear to affect accuracy on the microworld task, the self-report workload measures indicated that participants felt they had to work harder under conditions of interruption and auditory distraction in order to maintain that high level of performance. The Air Traffic Workload Input Technique (ATWIT; Stein, 1985, 1991) which measures workload in real time may be useful for future research to help pinpoint changes in workload that occur as direct result of interruption.

Although participants were explicitly told to ignore the background sound, it was apparent that they were unable to block it out completely. This may have been the case especially as the sound was not a continuous monotone auditory stream, but a natural conversation of meaningful (although irrelevant) speech that contained pauses, changes between speakers, and slight fluctuations in pitch to convey urgency, any of which may have captured attention. Interestingly, the effects of background sound did not universally impair performance on the microworld task relative to quiet; rather auditory distraction increased resumption lags and slowed decision-cycle times selectively during the post-interruption period. Thus the microworld task itself may not be susceptible to the negative effects of background sound, as participants for the most part were able to perform the task successfully managing the attention-capturing properties of the sound. However when interrupted, the specific processes involved in the suspension and resumption of task goals may be especially attention demanding, and thus compromised under conditions of divided attention.

Multiple Resource Theory (Wickens, 2002) predicts optimal time sharing between visual and auditory tasks but an impairment when modality is shared; indeed, performance on the microworld task was reduced by same-modality on-screen interruptions which is in line with the theory's predictions. However, Multiple Resource Theory would have difficulty in accommodating the finding that decision times were slowed to a greater extent – and resumption times were longer – when irrelevant auditory stimuli were also present, since auditory attentional resources should be separate to those deployed on the visual primary task.

The MFG model (Altmann & Trafton, 2001) can speak to the current results if a greater role of attention is specified. According to MFG, it is not the modality of the primary/interrupting tasks that is important, but the nature of opportunity for the strengthening and priming of associative cues (Ratwani, Andrews, Sousk, & Trafton, 2008). Auditory distraction (i.e., non-focused attention) appears to compromise the effectiveness of these processes. Altmann and Trafton (2002) suggest that strengthening and priming may be relatively automatic, but the fact that they are impaired under conditions of divided attention implies that these processes are effortful and require attentional resources. Salvucci (2010) also argues that interruption recovery is unlikely to be accounted for simply by the automatic reactivation of goals. He suggests that associative cues may be helpful to cue context, but real-world resumption lags (those in the order of several seconds) are likely to also involve deliberate and effortful reconstruction processes rather than just memory-based retrieval. Furthermore, given that in a dynamic task a lot of updating is necessary to regain SA, the role of attention may be important not just during the immediate resumption lag but throughout the whole of the post-interruption period.

Threaded cognition (Salvucci & Taatgen, 2008) may be able to offer further insight into the current findings, if one assumes that separate threads are associated with each of the primary task, the interrupting task, and the background sound. As expected, performance is slowed following interruption because the two on-screen tasks share the same peripheral resources; however, it is interesting that background sound – which prior to interruption caused no interference – now slows decision cycle times further. Auditory distraction should not conflict with threads from the primary or interrupting task in terms of perceptual resources (it is a separate modality) or motor resources (it does not require a response). It suggests that there is something about the nature of the background sound that clashes with task resumption processes and regaining SA, but not with ongoing performance of the microworld task. Threaded cognition makes a distinction between declarative cognitive resources and procedural resources (procedural skills for each of the tasks, as well as the skill needed to interleave them, such as swapping problem representations; Salvucci, Monk, & Trafton, 2009). A processing bottleneck may occur if two tasks both impose demands on the same procedural resource. The idea of a conflict of procedural rather than peripheral resources seems relevant to the concept of interference-by-process (e.g., Jones & Tremblay, 2000; Marsh, Vachon, & Jones, 2008). In accordance with this approach, interference arises not necessarily as a result of similar modality (visual, auditory) or code (verbal, spatial) but when two tasks share the same fundamental process, for example the processing of order information (Beaman & Jones, 1997; Jones & Macken, 1993) or the extracting of semantic information (Marsh, Hughes, & Jones, 2009). The *changing-state effect* (e.g., Jones, Madden, & Miles, 1992; Tremblay & Jones, 1998) posits that distinct acoustic changes present in the background sound automatically yield order information as part of a primitive, acoustic-based, perceptual organization process (Macken, Tremblay, Houghton, Nicholls, & Jones, 2003); it is possible then that this obligatory, pre-attentive seriation process occurring in the auditory stream clashes with order information inherent in the task of regaining SA, such as identifying and determining projected positions of aircraft, and prioritising the order in which they are managed.

Applying the MFG approach is more challenging in a dynamic C2 task because aspects of the environment will continue to evolve; how useful then are external cues to prime suspended goals if these environmental features have changed in appearance/location during the interruption? It makes sense that in these situations, participants must build up a general mental model of the task, and any pre-interruption preparation or strengthening may require anticipating the movement of items in the task, rather than simply encoding the current state of play. In this case, simply attending to an object would not be enough and it would need to be actively projected (Level 3 SA; Endsley, 1995). This would obviously impose a greater workload and it is likely that interruptions research looking at static tasks have underestimated the level of workload in real-world situations. In our task, the majority of first fixations following interruption did not reflect either the pre-interruption location of a previously attended object, or its projected position. However, the task did not include a warning period before the onset of interruption, and so perhaps participants were not able to engage in preparatory processes to any great extent. It may be interesting in future research to observe the nature of preparatory eye movements during a specific preparatory period or ‘interruption lag’ (Altmann, Trafton, Brock, & Mintz, 2003).

The current results demonstrate both the individual and interactive effects of interruption and background sound on C2 performance, and have key implications for the applied domain. Although an obvious aim would be to try to reduce the number of interruptions occurring in such critical work environments, many of these may be an unavoidable aspect of dynamic C2 operations and can sometimes convey critical information to the operator. This study suggests that an alternative way to reduce the negative effect of interruptions is to look at improving features of the external environment in which they occur, for example, by reducing the degree or nature of any background sound that may divert attentional resources. The addition of white noise can mask the acoustic properties of the sound so that any changes (e.g., voice, pitch, intensity, onset/offset) are less abrupt and less likely to capture attention (Banbury et al., 2001). A similar effect can be achieved by increasing the reverberation time of the background sound to create a ‘babble effect’ (Beaman & Holt, 2007; Jones & Macken, 1995). Alternatively, acoustic ceilings and partitions that absorb sound waves and decrease reverberation time can ‘soften’ the sound (Perham, Banbury, & Jones, 2007) and may lessen its attention capturing properties.

Another strategy to reduce the negative impact of background sound on interruption recovery might be to consider the role of attention and to develop support tools that can help direct attention towards critical aspects of the task. If auditory distraction hinders the reacquisition of SA following interruption, external aids that highlight important changes in the task environment may help focus attention and facilitate the recovery process. Examples include an instant replay device (Scott, Mercier, Cummings, & Wang, 2006) and the Change History EXplicit (CHEX; Smallman & St. John, 2003; St. John, Smallman, & Manes, 2005; but see Vallières, Vachon, & Tremblay, 2012) which logs all key changes in an easily accessible table. However, a problem with many support tools is that although one aspect of cognition may be augmented (e.g., change detection), another aspect may be impaired (e.g., speed of response; see, e.g., Vachon, Lafond, Vallières, Rousseau, & Tremblay, 2011). It is important therefore to use a holistic approach when designing an interruption recovery device, or indeed any decision support system. That is, rather than assessing isolated effects of a support tool on the particular variable that it is intended to augment, designers should use concurrent manipulations and measurements to gain an overall view of how that device affects all aspects of performance. It is possible that a specific improvement may also be accompanied by other gains or losses on other dimensions, and given the complex interplay of factors that characterize C2 operations, a holistic approach should be used to ensure that any support tool is truly beneficial (Lafond et al., 2010).

In summary, the current experiment highlights a number of issues that should be considered with regard to interruption recovery in complex and dynamic tasks. Slower decision making after interruption is likely to reflect reduced SA: Not only do participants need to reinstate previous task goals, but also update their mental model of the location/status of critical items in the vicinity, and assimilate the mismatch between pre- and post-interruption scenes. Participants are thus slower to identify and process relevant information in order to make a decision; and this is true to a greater extent (and for longer) when auditory distraction reduces attentional resources available for the recovery process. In laboratory-based tasks, the assumption is that following interruption all resources are available for interruption recovery, but this might not be the case in many complex, real-world C2 environments in which the impact of a given interruption may be influenced by other external factors. Although the task was not conducted in a real naval or air traffic control setting, the immersive environment of the microworld provides a valid approximation using non-experts that is likely to show similar effects (e.g., Nicholls et al., 2007; Parise, Imbert, Marais, & Alonso, 2012). Further research would be needed to determine if the importance of attention in interruption recovery was unique to dynamic tasks (due to higher task demands, more aspects to re-encode, and environmental changes affecting the use of associative cues), or whether it would also play a key role in recovery from static tasks. Nevertheless, we have demonstrated that task resumption is demanding and divided attention appears to impede this process, a finding that prompts the need to consider the role of attention in interruption recovery processes. Understanding the impact that external stressors can have on dynamic decision making will be important in assessing the type of support needed. The interactive effects of interruption and background sound observed in the current study indicate the importance of taking into account the wider context in which interruptions occur, in order to understand the mechanisms involved and provide support for cognition.

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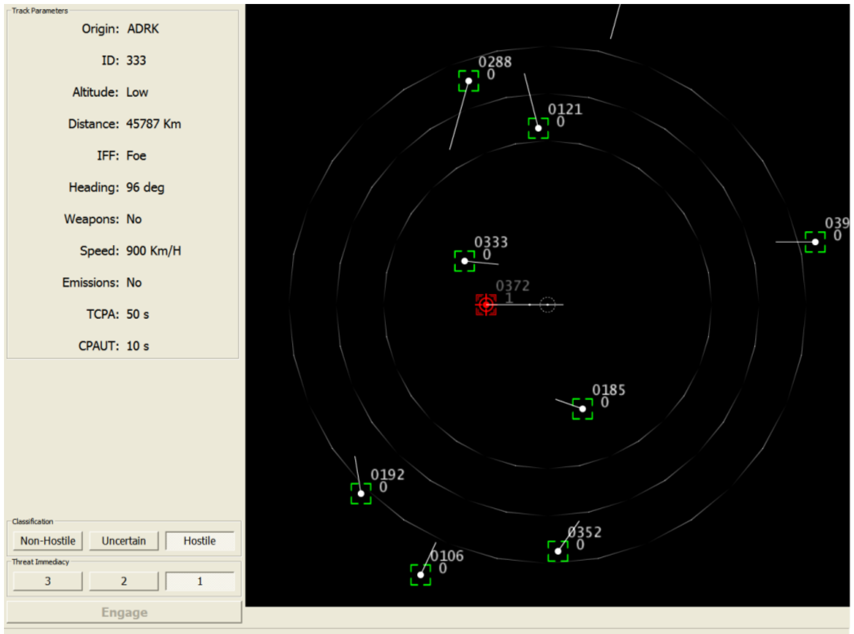

Figure 1. Screenshot of the S-CCS microworld visual interface. This interface can be divided into three parts: (a) a radar display depicting in real time all aircraft (represented by a white dot surrounded by a green square) moving at various speeds and trajectories around the ship (represented by the central point), (b) a parameters list providing information on a number of parameters about the selected aircraft, and (c) a set of action buttons allowing the participant to allocate threat level and threat immediacy to an aircraft and to engage with missile fire a candidate hostile aircraft.

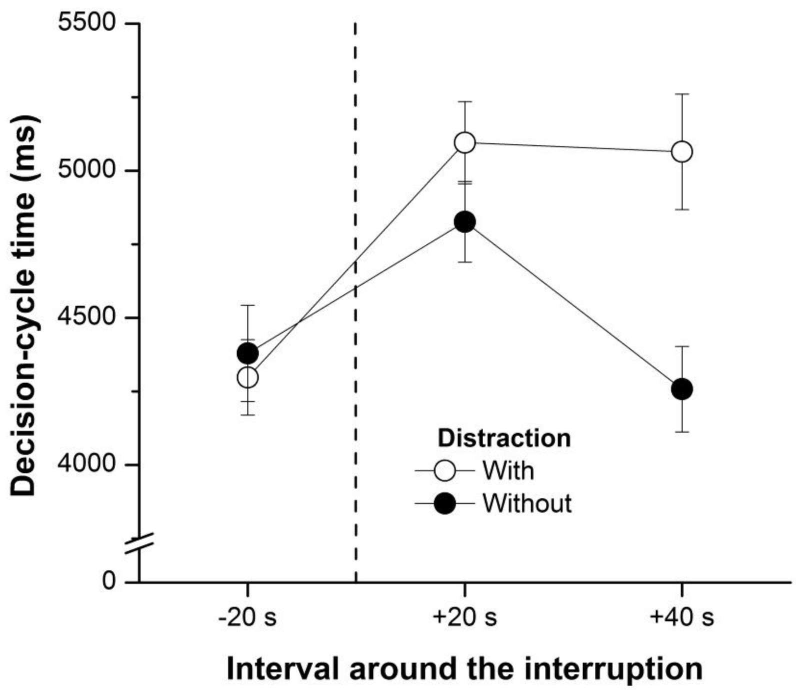

Figure 2. Mean decision-cycle time (ms) according to time interval around the interruption and the presence/absence of auditory distraction. Interruption line represents 24 s of time in the task. Error bars represent the standard error of the mean.

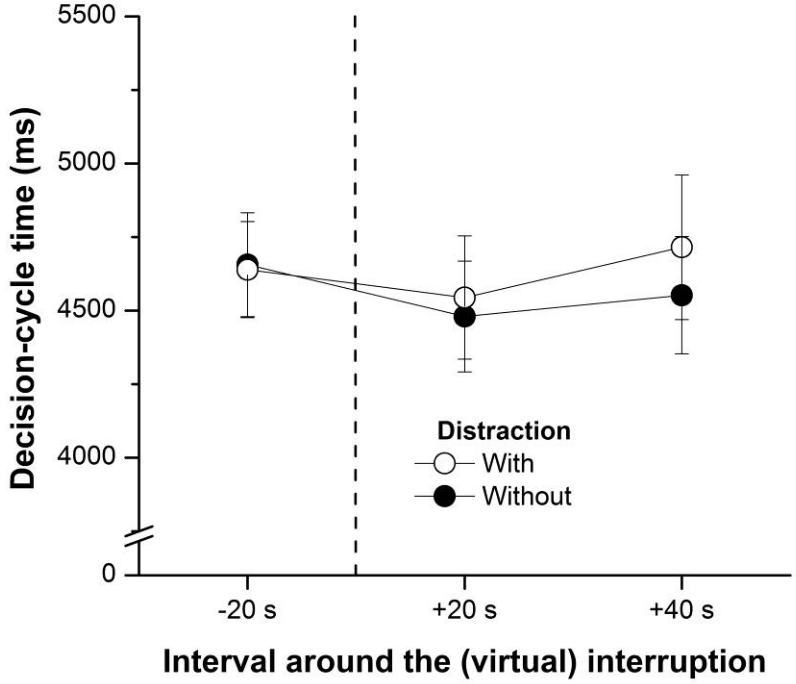

Figure 3. Mean decision-cycle time (ms) according to time interval around the ‘virtual’ interruption and the presence/absence of auditory distraction. The virtual interruption corresponds to the time around where the interruption would have occurred in the uninterrupted scenarios. Error bars represent the standard error of the mean.

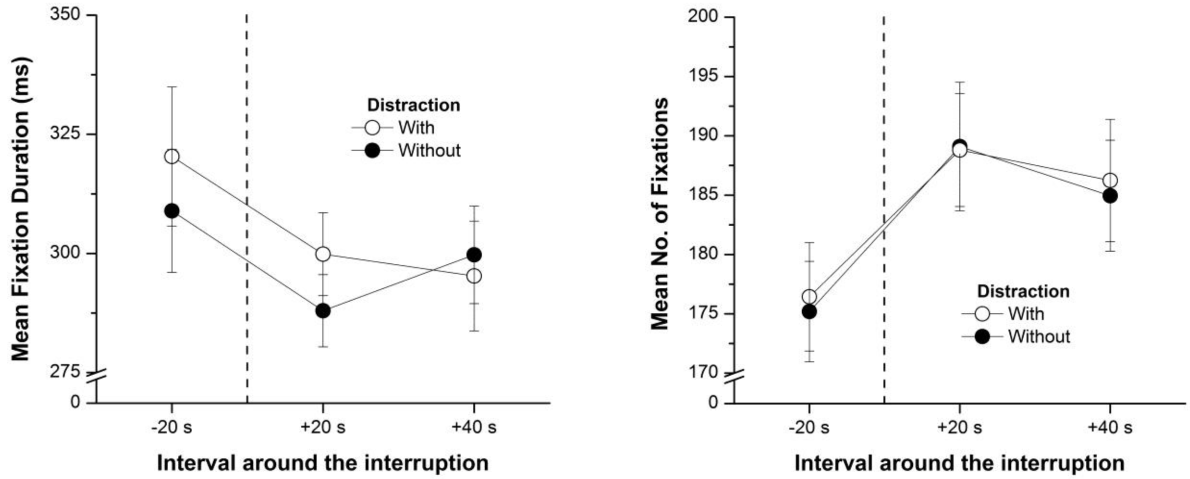

Figure 4. Eye movement data—mean fixation duration (ms) and mean number of fixations—according to time intervals around the interruption and the presence/absence of auditory distraction. Interruption line represents 24 s of time in the task. Error bars represent the standard error of the mean.

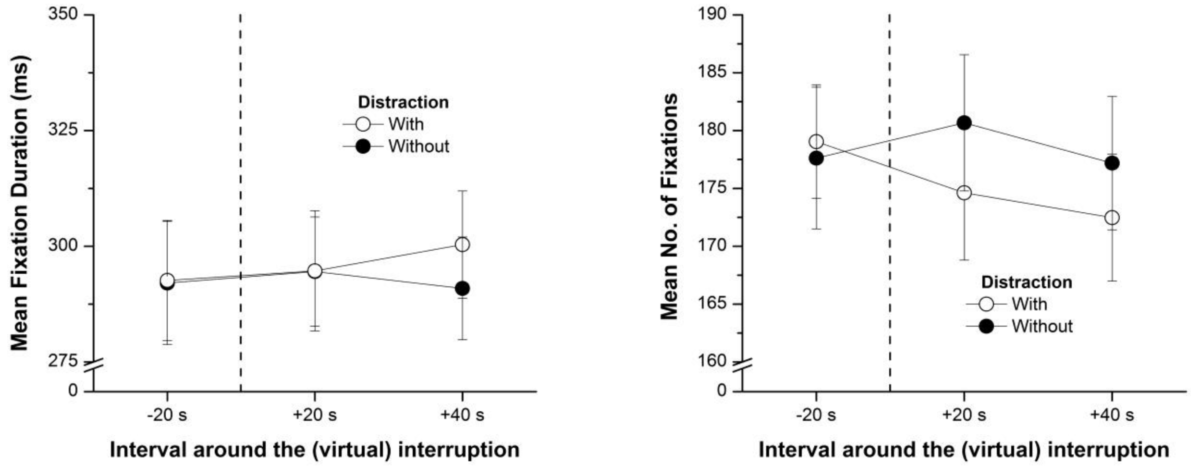

Figure 5. Eye movement data—mean fixation duration (ms) and mean number of fixations—according to time intervals around the ‘virtual’ interruption and the presence/absence of auditory distraction. The virtual interruption corresponds to the time around where the interruption would have occurred in the uninterrupted scenarios. Error bars represent the standard error of the mean.

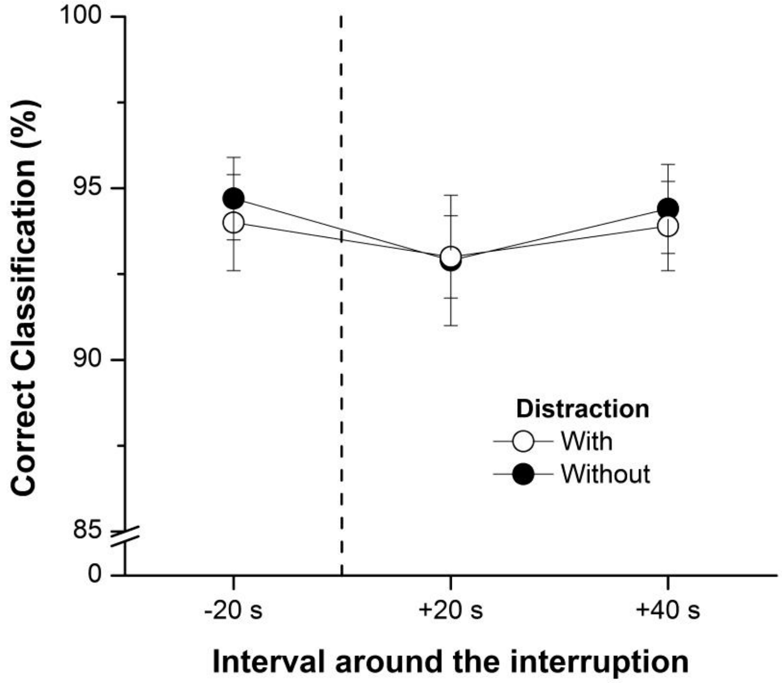

Figure 6. Mean classification accuracy according to time interval around the interruption and the presence/absence of auditory distraction. Interruption line represents 24 s of time in the task. Error bars represent the standard error of the mean.

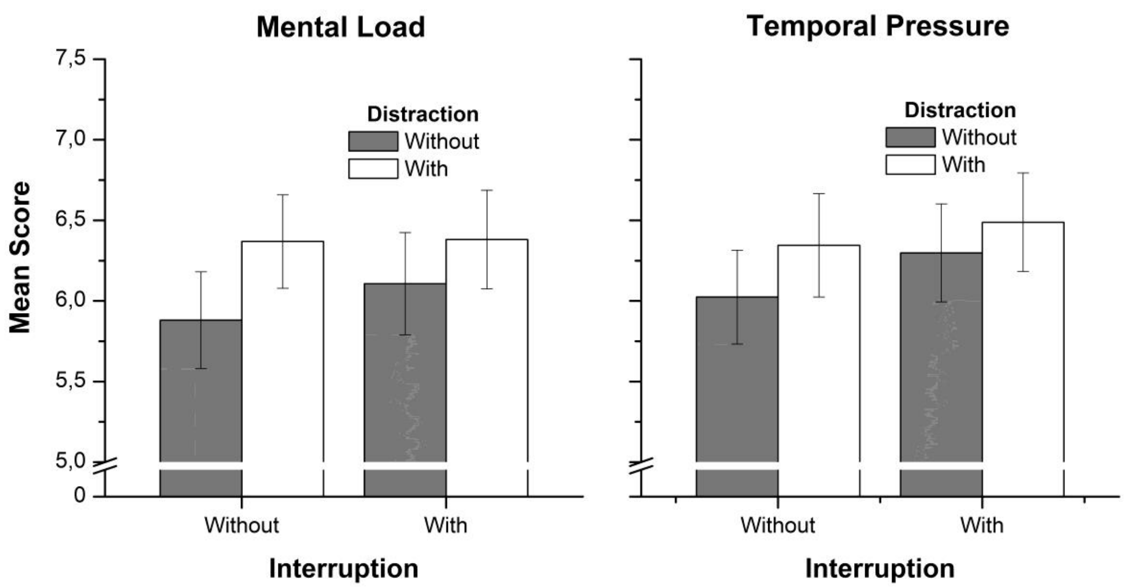

Figure 7. Mean mental load and temporal pressure scores in the presence/absence of interruption and auditory distraction. Error bars represent the standard error of the mean.