The Role of Time on Task in Multi-task Management

Robert S. Gutzwiller^a, Christopher D. Wickens^a, & Benjamin A. Clegg^a

^a Colorado State University, Department of Psychology, Fort Collins, Colorado, USA

Author Note:

Corresponding Author: Robert S. Gutzwiller, PhD; 777 6th Av, Unit 417, San Diego, California, USA, 92101; (254) 749-4559, robert.gutzwiller@gmail.com.

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Abstract

Extreme resistance to switching tasks can lead to cognitive tunneling. A four-attribute decision model of task management under load was recently built with an assumption of the resistance to switching tasks. Recent theory also suggests switch resistance declines with time on task, and this was tested in the current experiment. Participants managed sequential performance of four concurrent tasks in a multi-attribute task battery. The over-time trends in switch resistance, as related to both cognitive load, and stability of the tasks, were examined. Switch resistance showed no decrease over time overall, contradicting the existing theory. Instead, increases in switch resistance were found with an increased working memory load, and within periods of increased tracking task instability, shedding light on time-on-task effects and cognitive tunneling.

Keywords

Multi-tasking; time on task; task switching; task management; decision making

1 An aircraft pilot has just heard an explosion coming from the engines. Oil
2 pressure is dropping and temperature is rising. She is far from the airport, and must now
3 do high tempo multi-tasking. She must communicate the troubles to air traffic control,
4 consult navigational information to ascertain the nearest feasible landing site, diagnose
5 the seriousness of the problem, and determine whether it has cascaded to other systems
6 and, now flying in the clouds, assure that she maintains a wings level attitude. Four tasks
7 are confronting her in this overload period. How does she manage them and switch her
8 limited cognitive resources between them?

9 During periods of task overload, such as that above, operators will be confronted
10 by multiple tasks, and may find true time-sharing (concurrent task performance)
11 impossible, lapsing into a sequential processing, or task-switching mode. Under these
12 circumstances, they may engage in maladaptive “cognitive tunneling” (Dehais, Causse, &
13 Tremblay, 2011; Moray & Rotenberg, 1989), staying for a longer than desirable time on
14 an engaging task, to the exclusion of others.

15 Elsewhere (Wickens, Gutzwiller, & Santamaria, 2015), a model of discrete task
16 switching or task management has been proposed. The model predicts, within an
17 ensemble of three or more tasks: (a) the likelihood that an *ongoing task (OT)* will be left
18 (switched from) to move to an *alternative task (AT)*, and (b) which of the waiting
19 alternative tasks will be switched to. These choices are based upon a multi-attribute rating
20 of four task attractiveness features: ease (inverse of difficulty), priority, interest, and
21 salience. The degree to which these four attributes favor one task over the alternatives
22 predicts the likelihood that an alternative task is switched to, or (if it is the OT) that the
23 task promotes “staying”. In the experiment we describe below, our main interest is in a

1 potential influence of a fifth factor on switch likelihood, *time on task* (TOT). As the time spent
2 consecutively performing an ongoing task increases, we ask how the switch resistance to a suite
3 of alternative tasks may vary: in other words, to what extent will switching increase, decrease, or
4 fluctuate over time.

5 **Predicting the effects of time on task**

6 In terms of existing theory, a relatively strong argument has been made for decreasing
7 switch resistance (increased switches away from an OT) as a function of time on task (TOT).
8 Such a decrease in resistance (increase in switching) is based on two theoretically distinct, but
9 related arguments regarding cognitive and energetic effects. The cognitive foundation lies in
10 decision theory. Sheridan (1970; 2007) proposed that in multi-task environments, where an AT is
11 dynamic and perturbed by unpredictable influences in system state (an aircraft in turbulence, or a
12 toddler in the next room), increasing time spent on a concurrent OT will increase the uncertainty
13 of the state of this dynamic AT. The longer duration of time away from the dynamic AT
14 (increasing TOT on the OT), the greater the propensity to switch away from the OT to the
15 dynamic task (decreased switch resistance).

16 An energetics-based theory of the same phenomenon is the “effort depletion” concept of
17 Baumeister and his colleagues (Baumeister, Bratslavsky, Muraven, & Tice, 1998; Baumeister,
18 Vohs, & Tice, 2007). Baumeister et al. assumes that, particularly for more difficult tasks, the
19 cumulative effect of effort expenditure triggers a switch to take a needed break. While there has
20 been debate regarding the decision versus energetic mechanisms in the theory (Kurzban,
21 Duckworth, Kable, & Myers, 2013), Baumeister and Sheridan predict the same general trend –
22 with increasing time on task (TOT), switches away will become more likely.

1 From an alternative theoretical perspective, this change could be attributed to a
2 cognitive or meta-cognitive mechanism, an “opportunity cost” account espoused by
3 Kurzban et al. (2013). Experiencing increased effort, as demanded by the OT, serves as
4 an inhibitory signal that triggers a need to sample the alternative task, commensurate with
5 the increasing expected value associated with its performance.

6 Whether from loss of situation awareness, depletion of resources or increasing
7 value of a neglected alternative task, these three mechanisms imply decreasing switch
8 resistance. In contrast, an *increase* in switching resistance, which can fit loosely within
9 the memory for goals theory of interruption management (c.f., Altmann & Trafton, 2002;
10 Trafton & Monk, 2007), has also been suggested. Here, a goal state for an OT is
11 approached, and depends on information accumulation in working memory across an
12 epoch of time. The vulnerability of memory contents should induce a reluctance to
13 abandon the OT (e.g., switch to another task), if progress toward the goal would be
14 sacrificed. Consider the intuitive “just let me finish this paragraph” response to an
15 interruption while reading. In this case, reaching the end of the paragraph represents a
16 means to achieve the goal - a point of consolidation of the meaning of the words and
17 phrases contained within the paragraph (Kintsch & van Dijk, 1978). If interrupted
18 beforehand, the costs are numerous, in that, it may be difficult to resume reading in the
19 correct place, and it is unlikely the main idea of the paragraph will be retained.

20 The mechanism related to an increase in switch resistance may be relatively
21 insensitive to the length of the task, but there are often subtasks within a longer task. For
22 example, when temporary “subtask” boundaries are reached in an online purchase, e.g.,
23 entering the last digit of a credit card number, they often allow working memory to be

1 “dumped”, and maintenance of the relevant information for that subtask can cease. These are
2 points of subgoal completion in the memory for goals theory of interruption management, and
3 routinely serve as natural points of lowered workload (Iqbal & Bailey, 2005), and indicators it
4 may be optimal to switch tasks (e.g., Brumby, Salvucci, & Howes, 2007; Janssen, Brumby, &
5 Garnett, 2010; Monk, Boehm-Davis, & Trafton, 2004; Salvucci, 2005; Trafton & Monk, 2007).

6 Though we discussed the memory related aspects of task performance as related to
7 switching over time above, a parallel concept of *task stability* can be used to describe subgoal
8 completion boundaries in controlling dynamic systems. Stability derives from control theory
9 (Wickens, 1986). Dynamic systems have stable periods that allow operators to temporarily
10 neglect the specific task duties, often in order to address an alternative task. In driving, for
11 example, an optimal time to switch attention may be when the vehicle is centered in the lane
12 (low error), and not trending away from this position (low positive error rate). As these periods
13 fluctuate over time spent performing the task, so should switch resistance.

14 Whether these fluctuating periods of switching opportunity are created by memory, or the
15 stability of a system, the predictions are similar in that switching to an AT will be more likely to
16 occur *after* maintenance in memory ceases and task reach stable periods, rather than just prior. In
17 fact, in that prior period, switch resistance may *increase* leading up to the opportunity point,
18 something we call *task end-expectancy*. End-expectancy requires neither memory load, nor
19 stability fluctuations to induce the effect; instead, there must be anticipation, expectancy or
20 knowledge of the upcoming point that defines the “end” of the task, or subgoal, which then
21 influences planning of a switch (possibly increasing resistance, and tunneling, in anticipation of
22 an upcoming break in the task).

1 In summary, two opposing outcomes of increasing TOT have been proposed:
2 either increasing or decreasing switch resistance. *Decreasing* switch resistance over time
3 should occur whenever there are explicit costs associated with failing to update an AT
4 status, and/or when an OT becomes “effortful” over a sufficient amount of time. (In
5 vigilance tasks, and those imposing extreme mental demand, this can be as short as a few
6 minutes; Warm, Parasuraman, & Matthews, 2008).

7 In contrast, *increasing* switch resistance over time would be predicted in tasks
8 that impose working memory load, and may be associated with less monotonic
9 fluctuations in dynamic stability. The duration of the period in which that resistance
10 builds, and then “resets” can only be predicted by cognitive task or dynamic systems
11 analysis. Increasing resistance may also be predicted as a task end-expectancy effect,
12 when task/subtask ends can be anticipated, through either experience or perception.

13 **Task switching in a multi-task environment**

14 The current experiment employed the Multi-Attribute Task Battery (MATB II;
15 (Santiago-Espada, Myer, Latorella, & Comstock, 2011), a research software program
16 which measures operator performance on four concurrent tasks, an updated version of
17 MATB (Comstock & Arnegard, 1992). This platform has been used previously to
18 examine voluntary task switching in overload, individual differences in switching, and
19 the role of fatigue in switching (Clegg, Wickens, Vieane, Gutzwiller, & Sebok, 2015;
20 Gutzwiller, Wickens, & Clegg, 2014, 2015). Within MATB, a digital communications
21 task allowed us to examine memory load effects on switching. A dynamic tracking task
22 allowed us to examine task stability effects. Coupled with the two remaining tasks (a
23 process control task and a monitoring task), we examined the possible monotonic effects

1 predicted by effort depletion (Baumeister et al., 1998), and by opportunity costs (Kurzban et al.,
2 2013).

3 A final approach here was to examine the role of task difficulty, which we manipulated
4 between participants in the tracking task to examine the extent to which more difficult tasks,
5 requiring more effort, might show an enhanced “effort depletion” effect of increasing TOT. That
6 is, that with increased effort over time of a difficult condition, any increase in switching away
7 may be more substantial than under easier conditions.

8 We proposed several hypotheses:

- 9 • **H1a & H1b:** Fluctuations of state in the ongoing task of tracking and ongoing task of
10 communications will reveal TOT-related switching through changes in stability and
11 working memory demands. Specifically, (1a) when error, and negative error rate, are high
12 in tracking, switches away from tracking should be reduced, and (1b) as working memory
13 demands increase during the communications task due to information rehearsal, switches
14 away from the communications task should decrease.
- 15 • **H2:** To the extent that end-expectancy effects exist in this task, they will manifest as
16 fewer switches away from tracking, or communications, during the late epoch of ongoing
17 task performance. In part this is because the participant can view the upcoming “end” of
18 the task phase period for each task in the scheduler display (Figure 1).
- 19 • **H3:** To the extent that effort depletion and opportunity cost mechanisms are manifest,
20 this will be reflected in a decrease in switch resistance with an increase in TOT.
- 21 • **H4:** To the extent that effort depletion is causal, a more profound decrease in resistance
22 should be found when the task is more difficult (an interaction of TOT with ongoing task
23 difficulty on switching).

Methods

Participants

Seventy students at Colorado State University participated in this experiment, in return for optional, partial course credit; or were paid for the two hours of experimentation at an hourly rate of \$10. However, no participant received incentives for performance. The number of participants was set assuming a moderate rate of attrition and based on a prior study suggesting adequate power for switching effects (Gutzwiller et al., 2014).

Materials

A Dell computer with a standard mouse, stereo headphones, and a Logitech joystick were used for experimental presentation and manipulation of MATB II.

Figure 1. The MATB II interface. Four task areas, clockwise from top left: monitoring, tracking, resource management and communications.

MATB II is a primarily visual task environment (Figure 1), with the exception of the simulated, auditory control messages in the communications task. A description of the four main tasks is given in Table 1.

1 *Table 1: MATB Task and Interface Descriptions*

MONITORING
<p>Located in the upper left of the display, the <i>monitoring</i> task required participants to monitor for different types of events within the three main elements of the task. The first element is four vertical, randomly oscillating scale measures in the lower half. Each scale updates periodically and the participant attempts to monitor them to identify (by clicking on the particular scale) when any scale shows a steady “extreme” position, in either the uppermost or lowermost end of the scale. A second element, a green light is presented, which periodically turns off. Participants monitor this element to ensure the light remains on (clicking it, when it is detected to be off, which turns it back on). In the upper right corner, the final third element, a red light is presented as an onset event. Participants are asked to detect when the light is turned on by clicking on the red light button, which turns it off. In the current experiment, the monitoring task in MATB only presented events as red-light onset, and no scale or green light events were used.</p>
TRACKING
<p>In the upper center of the MATB display was a two-dimensional random input compensatory <i>tracking</i> task. Participants attempted to keep a circular reticle’s smaller, inner circle positioned on the intersection of the tracking displays X and Y-axes by providing inputs using a joystick. Tracking task difficulty was manipulated by varying tracking bandwidth (i.e., the rate at which the task changes over time, in this case increasing the bandwidth increases difficulty because the reticle is more likely to move off center). The tracking task was scored by measuring error in pixel deviations between the reticle center, and the center of the axes intersection (at 1HZ). Further, our MATB program recorded the X and Y-axis input activity from the joystick, enabling us to determine whether the joystick was in use, a novel addition to the program but one necessary for tracking participant activity and switches.</p>
SCHEDULER DISPLAY
<p>A task <i>scheduler</i> display, located in the upper right of the MATB display is a vertically advancing timeline with the horizon at the top of the display. The display visually indicates the beginning (upper portion of the red line), duration (green bar), and end (lower portion of the red line) of the tracking (denoted with a “T” on the right side) and communications task (denoted with a “C” on the left side). The display also shows the advancing overall time of the current trial.</p>
RESOURCE MANAGEMENT
<p>In the lower center of the display was a representation of a fuel <i>resource management</i> task aboard an aircraft. Participants attempted to maintain fuel levels (within a target level, seen in Fig. 1) in two depleting tanks (A and B) by controlling flow of fuel using pumps which directed flow to and from supplemental tanks. Pumps were able to be turned on/off to start and stop flow, and needed to be coordinated to maintain the threshold levels of the A and B tanks. Pumps siphoned fuel at various rates, listed on the right hand side of the resource management display. Events in the resource management task were constrained to two different pump failures (pump 1 and pump 3); when a pump failed the pump turns red and is unable to be turned on until a 30s time period elapses, forcing the participant to compensate through other pumps and fuel tanks.</p>

COMMUNICATIONS

The *communications* task, located in the lower left of the MATB display, simulated a pilot interacting with air traffic controller requests. Events were auditory messages presented to participants, beginning with a call sign to denote their intended recipient, and conveyed an instructed action. When the message was directed to a participants' call sign, "NASA 504", participants responded via mouse in the visual display in the lower half of the communications display. The call sign was the same over all trials, and was further displayed in the upper center portion of the communications task display. Upon hearing instructions, participants were told to select one of four radios and then change frequencies to a new value, given in the auditory message. The frequency information required rehearsal in working memory if it was not immediately entered, and at five digits represented a significant load. The task was completed when a final "enter" button was clicked. In general, the communications tasks takes about 15-20s to complete. Presentation time of the task event was jittered (e.g., slightly randomized in a distribution around a main starting point in time) so that events would be less predictable.

1

2 Experimental Design

3 As subjects performed the four tasks of the MATB, two constraints were imposed. First,
 4 only a single hand was employed for input on all tasks, thus preventing the subjects from
 5 concurrently responding. Second, the communications task and the tracking task were alternated
 6 and never occurred at the same time, as it would have otherwise been impossible to infer where
 7 processing was engaged between these two tasks.

8 To test the various TOT theories, an interruption-inspired experimental design was used.

9 The tracking and communications tasks were conceived as ongoing tasks during interchanging
 10 phases (see Figure 2) for the purposes of interrupting them with events from one of the two
 11 remaining alternative tasks, monitoring or resource management. In total for each trial, there
 12 were six repeated interchanges between these OTs. Alternative task events, as outlined in Table
 13 1, took the form of either a red light onset (monitoring), or a pump failure (resource
 14 management). One of the AT events occurred randomly at one of three time epochs defined
 15 during each phase of tracking, and each phase of communications task (Figure 2). Although it

was twice as long, the tracking phase had the same number of alternative task event interruptions as the communications phase to ensure comparable number of opportunities to switch.

Though we describe AT event onsets as *interruptions*, events were not mandatory to respond to and OT performance was not forced or stopped. Instead, MATB was made to record participant responding on all tasks. Given the instructions, when task performance was recorded as changing between tasks, the time of the switch and direction (*from* what task, *to* what task) was also recorded. Thus, during the time of an OT tracking phase, for example, we were able to assess when participants began tracking performance as evidenced by joystick axis deviations; then we could look at switches away from the tracking task. These methods provided us with evidence (a) participants had been performing tracking previously and allowed us to (b) determine which task was switched to when participants interrupted this performance. Using this logic we were able to examine aspects of TOT switch behaviors.

Figure 2. Example timeline for a test trial in the experiment, showing the interchanging

communications (C) and tracking (T) task phases. In the exploded section, the approximate time epochs of early, midway and late are shown for each task. One epoch is chosen for each phase for an AT event presentation. These occur in each epoch, randomized, but only once per task phase.

The tracking task was active for 1 minute during each tracking task phase, and expended time defined “early” (0-20s), “midway” (20-40s) or “late” (40-60s) epochs (Figure 2).

In the communications phase, epochs were defined to provide “boundaries” for the increasing working memory load induced by the task over time. During each communications task, encoding of call sign information (early epoch) was followed by encoding of the radio and frequency information (midway epoch), and 0-10s from the end of the midway epoch during the period of expected WM rehearsal defined the late epoch. The precise time for epoch varied as a function of the unique audio recordings and their properties (e.g., when information was audible, how rapidly the speaker announces the information, and whether or not pauses in speech occurred; Gutzwiller, 2014).

Procedure

Participants began by reviewing training material explaining the MATB environment for ten minutes, using a set of slides derived from the MATB II manual. Re-viewing materials was allowed during the ten-minute period, but only after all slides were viewed. A two-minute training trial in MATB, in which participants attempted to perform all four tasks, was then completed with instructions that all tasks had equal priority, and, that only a single hand could be used to respond using the mouse or joystick.

After training trial completion, participants were randomly assigned to one of two conditions: either easy, or difficult tracking task. All other events in each of the trials same, including phases of ongoing tasks and alternative tasks. Participants completed six trials in the MATB simulation, each lasting 10 minutes.

During MATB performance, participants switched freely between the tasks with no assigned priority. A task switch was measured by examining control activity across tasks; when control activity ceased in one task and then subsequently began in a new task, a switch from one to the other was recorded along with the trial time of the switch (as discussed in the Experimental Design section above). For switches from OT to AT events, the events presented the only opportunity to respond to that AT during the epoch (e.g., early middle or late). Thus, despite the difference in length between the tracking and communications OT, the opportunity to switch to AT were equivalent between them).

Before and after completing the test trials block, participants completed an attribute rating survey (Gutzwiler et al., 2014) by rating which of two tasks were more difficult, higher priority, or was of greater interest. These rating data are the focus of other work. Finally, participants completed the attentional network task, a measure of individual differences in executive attention (ANT; Fan, McCandliss, Sommer, Raz, & Posner, 2002). For space, we describe those results elsewhere, but, increased executive control as measured by the ANT increased the exploitation of natural points of task stability for switching away from the tracking task (Gutzwiler et al., 2015).

Results

In this manuscript we report the bulk of the findings from this experiment, offloading two elements to other documents. First, the performance data for each of the MATB tasks (excluding tracking), as they are not the focus here, can be found in a dissertation (Gutzwiller, 2014, Experiment 2 Results, Table 5.2). The second omission refers to the data and findings associated with the performance of the ANT task, which can also be found in the dissertation (Gutzwiller, 2014, Experiment 2 Results) and in a published proceedings paper (Gutzwiller et al., 2015).

Programming errors resulted in data loss for six participants. Three additional participants had tracking error >3 SD of the group means, and their data were discarded. All analyses were on the remaining 61 participants unless otherwise indicated. Where sphericity was violated based on Mauchly's W reaching significance at $p < .05$, Greenhouse-Geisser corrections were used. Tracking performance data are discussed here; performance from other tasks are omitted for brevity (but see Gutzwiller, 2014).

Task Switching

First we examined the role of tracking task difficulty. Error in the tracking task was assessed in a 2 (difficulty) $\times$ 6 (trials) repeated measures ANOVA. There was a significant main effect of task difficulty (see Figure 3), such that the easy tracking condition had less error ($M = 17.45$) than the difficult task ($M = 32.57$) overall ($F(1, 60) = 135.59, p < .001, \eta_p^2 = .70$). There was also a main effect of practice such that error decreased over time ($F(3.362, 201.707) = 32.83, p < .001, \eta_p^2 = .35$). A significant interaction suggested that the benefit of practice was

- 1 greater for the difficult condition than for the easy tracking condition ($F(3.362, 201.707) = 6.60$,
 2 $p < .001$, $\eta_p^2 = .10$), and this trend is visibly confirmed in the first two trials.

3
 4 **Figure 3.** The average tracking error RMSD for each condition (easy, dotted green line; and
 5 difficult, solid red line), across each of the trials. Error bars are standard error of the mean.

6
 7 Therefore, in the tracking task the effect of difficulty and practice are both evident, and
 8 suggest the difficulty manipulation was effective. A 2 (OT; tracking or communications) x 2 (AT
 9 event; resource management or monitoring) x 3 (TOT; time epoch of event occurrence – early,
 10 midway, or late) x 2 (difficulty condition) repeated measures ANOVA was conducted on number
 11 of switches made to alternative task events. Switches were scored as the first response to the AT
 12 task originating from the OT of interest before the AT task timed out (~10s). Thus, despite the
 13 longer amount of time spent tracking, the same opportunities for a switch to an interrupting task
 14 were present (a total of 6 on average). The results showed that difficulty condition had no main
 15 ($F < 1$) or interactive relationship with task phase ($F < 1$), or AT ($F < 1$). Tracking difficulty was

only marginally interactive with OT ($F(1,58)=4.00, p=.05, \eta_p^2=.06$). Tracking difficulty was therefore removed from our factor list and the analysis was rerun.

Tracking was more likely to be interrupted ($M=4.17$) compared to communications ($M=2.73; F(1, 59)=108.75, p=.001, \eta_p^2=.65$). Monitoring events were more powerful interrupters ($M=4.81$) compared to resource management events ($M=2.08; F(1, 59)=561.51, p<.001, \eta_p^2=.91$). Fewer switches were also made over time, from early ($M=3.95$) to midway ($M=3.45$) to late ($M=2.94$), regardless of the ongoing task, or AT event type ($F(2, 118)=35.46, p<.001, \eta_p^2=.38$). This main effect for time epoch provides evidence of a general *increase* in switch resistance over time, and appears to reject H3 (the general decrease in switch resistance over time hypothesis of Baumeister and Sheridan).

Interactions between time epoch and OT ($F(1.694, 99.948)=36.11, p<.001, \eta_p^2=.38$), time epoch and AT ($F(2, 118)=35.90, p<.001, \eta_p^2=.38$), and between OT and AT ($F(1, 59)=6.35, p<.05, \eta_p^2=.01$) were all significant, but superseded by a significant three-way interaction, depicted in Figure 4, between time epoch, OT type, and AT type ($F(1.821, 107.414)=32.73, p<.001, \eta_p^2=.39$). The three-way interaction is the focus of our analysis, and we examine it by considering the differences in the two-way interaction effects between AT “interruptions” in the tracking and communications phases. We plot these in terms of opportunity; that is, percentage of AT events switched to as a function of how many were possible for each OT and AT (see Figure 4). The percentage was chosen to illustrate how many AT events were also neglected during different periods.

Figure 4. A three-way interaction for the percent of average switches from each ongoing task (percentage out of 6 possible, for each epoch and AT). Tracking (left panel) and communications (right panel) are plotted by each AT of monitoring (green, dashed) and resource management (black, solid) over the epochs of interruption (early, midway and late in each panel). Error bars represent standard 95% confidence intervals for the interaction.

In the left panel of Figure 4, when tracking is the OT, interruptions by the resource management or monitoring task show no evidence of change over time. And although more switches were made to the monitoring task, no interaction between AT event and time on task was found ($F(2, 120) = 2.30, p = .10, \eta_p^2 = .04$). In stark contrast, for the communications OT task in the right panel, interruptions by monitoring AT show a marked decline of 61% over time ($F(2, 120) = 62.50, p < .001, \eta_p^2 = .51$). Switch resistance from communications to monitoring interruptions builds over time, due to working memory buildup, as we see switches decrease (*H1b*). Far more modestly, switches decrease from communications to the resource management AT, with only a 32% decrease in switching. The bulk of this effect is the building from the first

to the second period (in contradiction of a predicted end-expectancy effect, where it should have been seen from the second to the third, a partial failure to support *H2*).

Addressing the other theoretical mechanism predicted to underlie declines in switching over time, the opportunity cost theory proposed by Kurzban et al (2013), we must first consider that there was no decline in resistance at all. The pattern of interaction in the right panel of Figure 4 is at least partially consistent with differences in opportunity costs: switches to resource management are somewhat preserved over time, while switches to monitoring decrease drastically. We would anticipate this pattern if there were greater value (reduced opportunity cost) of switching to resource management, than to monitoring: this difference can indeed be inferred from participants' ratings of attributes). As shown in Table 2, attribute ratings were calculated by averaging how each task rated against each of the others along a range of -3 to +3 for each pair, where a value of 0 indicated no clear subjective advantage to either task in the given pair. Thus a task that clearly won (higher values) on each element – priority, interest, and difficulty (which was reverse scored), was deemed more subjectively attractive when these elements were summed.

Table 2. Task attribute ratings. More positive rankings = higher task attractiveness for Priority and Interest, but *lower* attractiveness for Difficulty. 95% CI's shown in parentheses.

	Priority	Interest	Difficulty
Tracking	-0.07 [-.25 to .12]	0.45 [.27 to .64]	Easy: -0.17 [-.45 to .11] Hard: 0.28 [0.0 to .57]
Resource Management	0.68 [.51 to .85]	1.14 [.95 to 1.32]	1.51 [1.34 to 1.68]

Monitoring	-0.87 [-1.06 to -.69]	-1.68 [-1.82 to -1.55]	-1.48 [-1.63 to -1.31]
Communications	0.27 [.06 to .47]	-0.79 [-.98 to -.61]	-0.11 [-.29 to .07]

1

2

3 That is, participants considered the resource management task to be of modestly

4 higher priority (.68 vs. -.87), and of far greater interest (1.14 vs. -1.68) than monitoring,

5 these two attributes contributing to what we might describe as objective and subjective

6 “value”, respectively (Table 2). Hence when the operator is performing communications

7 the opportunity cost to switch to monitoring declines. Nevertheless, those costs driving

8 the switch to a more valuable (higher priority, more interesting) resource management

9 event are at least preserved across the three phases.

10 Of the two theories predicting an increase of switching over time, we find no

11 evidence for effort depletion across the longest (~10 minute) period where multiple tasks

12 were active. We did find evidence for opportunity costs, but only within the switches

13 **Task Stability**

14 Attempting to determine optimal times to switch has been done using a variety of

15 methods, including cognitive modeling for task interleaving (Janssen, Brumby, Dowell,

16 Chater, & Howes, 2011). However, although we expect such methods to generalize to

17 more than dual-task settings, we have employed related method below to examine

18 tracking task performance.

Tracking error magnitude (categorized as low, medium or high based on tertiles) for each trial was calculated over each participant's tracking phases. The rate of error change: increasing (+), decreasing (-), or not changing (0), was determined by the temporally preceding error magnitudes. Data were binned into two categories, which we labeled "locally optimal" (when error was low and rate was (-) or 0), and "resistant" (when error was high and rate was (+) or 0).

Only the data from the first three difficult tracking trials were examined, a restriction justified for two reasons. First, the difficult category represented the best chance to find operators using natural break points because difficulty enhances the subgoal switching effect. Second, the earliest trials were examined because learning curves indicated considerably less tracking skill earlier (i.e., Figure 3), and hence participants may have placed a greater premium on avoiding switches at high demand (resistant) periods. Classification was done separately for each participant's data, to reflect the role of individual differences in skill and strategy.

A paired two-tailed t test showed more switches away from the tracking task were made during the *locally optimal* conditions ($M= 7.85$) compared to the *resistant* ($M= 6.0$) conditions ($t(38)= 2.38, p= .02$), highlighting the state space data as predicting a task switch in line with a fluctuating effect of time on task ($H1a$).

Discussion

In many domains, operators are occasionally confronted with overloading conditions. We refer back to the overloaded emergency conditions the pilot faced during engine troubles. Predicting how attention is allocated during these events is a challenge. In particular, determining the features of the task environment which cause operators to "stay" in tasks, and which cause them to switch is useful for design. The current study focused on changes in

switching that arise over time spent performing a task, which in addition to other aspects in the STOM model (Wickens et al., 2015) may govern task switch behavior.

Our first two hypotheses regarding the dominant role of temporary phases within a task in availing “switching opportunities” were well supported, by results from the communications task and tracking. Our findings in the communications task were consistent with memory for goals theory (Altmann & Trafton, 2002); people are reluctant to switch when a subgoal for the task remains in working memory and are more likely to switch once that information has been “dumped”, a more locally optimal switch time (e.g., Janssen & Brumby, 2010). However, this effect is only prominent when the interrupting AT is of low perceived priority and interest (in this case, the monitoring task). Switch resistance remains high and constant when the more difficult task of resource management is presented. For communications, these switch times were monotonically changing across the 30-second segment.

For tracking, opportunities fluctuated unpredictably, but these too showed an opportunistic “invitation to switch” when tracking was stable (and see Gutzwiller, Wickens, & Clegg, 2015). Our use of state space to examine tracking (see Wickens, 1986; Wickens, Hollands, Banbury, & Parasuraman, 2013) also helped determine when ‘locally optimal’ periods for switching away from a tracking task occurred. These opportune times resulted in 30% more switches away from tracking, a finding in line with much of the research on task and goal state boundaries.

Our second hypothesis that examined for an “end expectancy” effect was unconfirmed. An end effect would have been most evident in the tracking task, with a clearly visible “end” to each phase signaled in the scheduling display. Yet, Figure 4

1 indicates there was no trend for a decrease in switching from tracking as this end approached.

2 Hypothesis 3 concerned evidence for decreasing switch resistance across a task. For the
3 shorter duration 30-second trial segment of communication, the confirmation of our first
4 hypothesis by definition disconfirms the opposite trend of H3; and for the 1-minute tracking
5 duration episodes, we have already noted the absence of any trend when examining for end
6 effects in H2. Further doubt for effort depletion was cast by the absence of any interaction of
7 TOT with tracking difficulty: switches away from tracking with TOT did not increase when
8 tracking was more difficult. However, the theories discussed here do not specify a timeframe for
9 the emergence of these effects, so we are limited in our ability to make a strong conclusion.

10 In the current results, the fact that the critical difference in this interpretation lies in the
11 difference between the left and right panels of Figure 4 demands we assess the various ways that
12 the two ongoing tasks (tracking and communications) differ that might (a) cause the
13 communications task to be more switch resistant overall, and (b) be the only one of the two tasks
14 to show **increasing** switch resistance with TOT. We attribute this to three interrelated features of
15 the communications task not shared by tracking: first it is auditory, while tracking is visual;
16 second, communications has a strong working memory component; in part because it is auditory,
17 it is not possible to go back and review or recheck information as would be possible with visual
18 text. Tracking of course has no such working memory component. And third, the goals of
19 communication are transient and unique to each message whereas tracking has a single ongoing
20 goal (minimize error). As such, the interruption/switching behavior of communications
21 (particularly from the monitoring event) is fully consistent with the memory-for-goals theory of
22 interruption management (Altmann & Trafton, 2002); that of tracking is not. An objective of

1 future research should be to unconfound these three features of difference between the
2 two ongoing tasks, to assess which may be most responsible for the differences in switch
3 resistance.

4 Also noted is that, given the importance of ongoing and persistent engagement in
5 these tasks to elicit the overload state, a measure of mind wandering or disengagement
6 with an ongoing task (e.g., Smallwood & Schooler, 2006) may be interesting to
7 incorporate into future investigations. In particular, given a focus elsewhere on the
8 relationship between individual differences in executive control and switching in this
9 paradigm (Gutzwiler et al., 2015), one might predict that it is in part related to
10 differences in mind wandering frequency and the difficulty of the ongoing task (Kane,
11 Kwapil, Mcvay, & Myin-germeys, 2007).

12 **Practical Application**

13 Our findings overall suggest operators would be less likely to interrupt tasks
14 during periods of task instability, and memory overload, perhaps especially so in the face
15 of more difficult interrupting task events. While some amount of optimality has been
16 shown in these types of decisions (Brumby et al., 2007; Janssen, Brumby, & Garnett,
17 2012; Janssen et al., 2010), the prior results are only within pairs of tasks: not more than
18 2 tasks as we show here, an important contribution that aids scaling this research into new
19 domains in the real world.

20 These findings suggest we are on the right track to explaining, and eventually
21 predicting “tunneling” types of effects, when switching may be precluded altogether
22 (Dehais et al., 2011). Further evidence for resource depletion must be sought using a

longer time on task, and for opportunity costs, sought with a more explicit representation of the diminishing (or increasing) rate of returns on task performance, as time passes.

Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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