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The Coffee Challenge: A new method for the study of everyday action errors

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Errors in everyday activities pose significant consequences for individuals with mild cognitive deficits. However, there are few performance-based methods available to study action in these populations; the Coffee Challenge (CC) was designed for this purpose. Experiment 1 examined CC performance in healthy participants across 10 practice trials. Analyses showed evidence for routinization after 10 trials. In Experiment 2, CC performance was disrupted by dividing attention. Errors increased significantly, but performance was not qualitatively different from baseline. The results shed light on action impairments in patient populations and validate the CC as a promising new tool for future studies.

INTRODUCTION

Errors in everyday tasks, such as grooming and meal preparation, are known to occur in healthy individuals, especially when working under conditions of sleep deprivation, time pressure, and divided attention. Individuals with mild neuropsychological impairment, as in attention deficit disorder, mild traumatic brain injury (TBI), and early stages of dementia are even more vulnerable to high error rates on everyday tasks. Quite often, action errors pose negative consequences for employment and independent living in such high functioning populations (Asikainen, Kaste, & Sarna, 1996; Nadeau, 2005). In individuals with moderate to severe neuropsychological deficits, action performance may be more seriously impaired and linked to numerous negative outcomes, including institutionalization, depression, and death (Adam, van der Linden, Jullerat, & Salmon, 2000; Hargrave, Reed, & Mungus, 2000; Knopman, Berg, & Thomas, 1999; Noale, Maggi, & Minicuci, 2003). Studies by Schwartz and colleagues (Schwartz, Buxbaum, Montgomery, Lee, & Coslett, 1999; Schwartz et al., 1998) have shown that action deficits in moderately to severely impaired neuropsychological populations may be best understood as an exaggeration of the normal tendency to commit errors of action in states of fatigue or distraction, when cognitive resources are diminished. However, very few studies have examined everyday action performance in healthy and high-functioning individuals (see Rosenbaum, 2005), and the link between resource limitations and naturalistic action errors in these populations remains unclear.

One reason for the dearth of action research in healthy populations is the lack of valid experimental techniques for eliciting and observing errors on familiar, well-practiced tasks in the laboratory. Thus, the primary objective of this paper is to present a novel laboratory method for the study of action errors in healthy or high-functioning participants. A secondary goal is to relate our preliminary

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results with this new method to the study of action impairment in neuropsychological populations.

Past studies of action errors in high-functioning individuals have relied heavily on interview and diary methods. Although these reports have generated a wealth of descriptive information (Broadbent, Cooper, Fitzgerald, & Parkes, 1982; Norman, 1981; Reason & Mycielska, 1982; Sellen & Norman, 1992), self-report techniques are prone to bias from recall/monitoring failures and rater characteristics, and they afford no opportunity to explore causal mechanisms. Shallice and Burgess (1991) have developed naturalistic tasks that assess planning and problem solving for mildly impaired patients, but these methods do not address the breakdown of action and object selection that occurs on highly familiar tasks that do not require problem-solving abilities. Most performance-based methods of everyday tasks have been designed for and used with moderately to severely impaired clinical populations. For instance, the Naturalistic Action Test (NAT; Schwartz, Buxbaum, Ferraro, Veramonti, & Segal, 2003; Schwartz, Segal, Veramonti, Ferraro, & Buxbaum, 2002), a standardized measure that requires participants to complete goal-directed tasks in various contexts, has been useful in characterizing action impairment across a wide range of clinical populations, but does not simulate conditions in which healthy/high-functioning individuals are prone to error. Thus, healthy and many high-functioning participants perform at or near the maximum possible score on the NAT.

Humphreys and colleagues (2000) reported a divided-attention manipulation to increase task demands and elicit errors in healthy participants on familiar, naturalistic tasks, such as sandwich making and gift-wrapping. An articulatory suppression task (i.e., repetition of the word "the") or a more difficult, attention-demanding task (i.e., oral version of the Trail Making Test[1]) was simultaneously performed with the everyday tasks. Participants who performed the more difficult concurrent task made more action errors than those who performed the articulatory suppression task, suggesting that a concurrent task paradigm is useful for eliciting errors on naturalistic tasks in the laboratory. However, participants were not well practiced on the primary tasks, and performance without the concurrent task was not reported. Without baseline data, one cannot assess which errors were promoted by the concurrent task or address why errors increased when attention was divided.

To address the limitations in existing methods, we have developed a novel variant of the coffee-making task that has featured in patient studies (Hartman, Goldenberg, Daumüller, & Hermsdörfer, 2005; Schwartz, Fitzpatrick-DeSalme, & Giovannetti, 1995a; Schwartz, Reed, Montgomery, Palmer, & Mayer, 1991) and computational simulations (Botvinick & Plaut, 2004; Cooper & Shallice, 2000). Termed "Coffee Challenge" (CC), the task requires individuals to use common objects to achieve a familiar goal under conditions known to encourage action errors. These include: (a) multiple subgoals that require sequencing (Mattson & Baars, 1992; Norman & Shallice, 1986; Reason, 1979); (b) time pressure (Mattson & Baars, 1992); (c) an array of functionally and visually similar distractor objects (Cooper, Schwartz, Yule, & Shallice, 2005; Cooper & Shallice, 2000; Giovannetti, Libon, Buxbaum, & Schwartz, 2002a; Schwartz et al., 1998); and (d) object location uncertainty (Luck, Hillyard, Mouloua, & Hawkins, 1996; Manjeshwar & Wilson, 2000). Specifically, the CC required participants to make two cups of coffee (>1 goal) in a sequence of their own choosing, as quickly as possible, and without making errors.

In real life, even very routine tasks are prone to error under particular conditions. The aim of Experiment 1 was to familiarize participants with the CC over 10 practice trials. Performance was examined for evidence of improvement and expertise on "late" versus "early" practice trials. Then, in Experiment 2, we attempted to disrupt CC performance in the same group of participants using a divided-attention procedure designed to simulate a naturalistic secondary task (e.g., a compelling conversation). In Experiment 2, participants performed the CC with and without a concurrent task. Performance was compared across conditions to determine whether (and how) divided attention disrupted CC performance. In the General Discussion we review the implications of our findings for understanding naturalistic action impairment in clinical populations. Of particular interest is whether or not performance in the divided-attention condition would simulate naturalistic action impairment in patient populations, as suggested by the resource theory.

EXPERIMENT 1: THE EFFECT OF PRACTICE

It frequently has been demonstrated that well-practiced, routine naturalistic tasks are performed

[1]The Oral Trail Making Test (Abraham, Axelrod, & Ricke, 1996; Ricker & Axelrod, 1995) requires participants to alternate between reciting the alphabet and counting (e.g., A–1, B–2, etc.). Humphreys et al. (2000) modified the task by requiring participants to begin with an arbitrary number–letter pair (e.g., D–8, E–9, etc.), rather than always starting with A–1.

more quickly and with fewer errors than novel, unpracticed tasks (Schwartz et al., 1999; Schwartz et al., 1998; Schwartz et al., 1995b; Schwartz et al., 1991; Sellen & Norman, 1992; Shallice & Burgess, 1991; Sirigu et al., 1995). We administered the CC over 10 trials and compared performance on Trials 1–5 (early practice) to performance on Trials 6–10 (late practice). Our first prediction was that participants would make fewer errors and show faster completion times in late practice than in early practice.

In contrast to novice performance, well-practiced or expert performance appears to be governed by knowledge structures (or schema/action plans) and requires fewer processing resources (Bedard & Chi, 1992). Studies of language (Dell, Burger, & Svec, 1997) and sequential motor skills (e.g., piano playing; Palmer & Drake, 2000) have shown that as practice strengthens the influence of a higher order plan (or schema) on behavior, the proportion of sequence errors that are anticipations increases (the anticipatory practice effect). According to Dell et al. (1997), higher order plans facilitate the activation of future steps, but do not influence the deactivation of past steps. Deactivation occurs automatically via self-inhibition (see Houghton, 1990). In other words, the probability that an error will involve premature performance of a future step (i.e., an anticipation error) increases as the action plan is strengthened with practice, but practice has no direct effect on perseveration probability. We hypothesized that practice would strengthen the influence of the action plan on performance; therefore, our second prediction was that the proportion of sequence errors that are anticipations (anticipation proportion) would be larger in late practice than early practice.

Studies of action impairment in neurologically impaired populations have shown qualitative differences in error patterns that may be related to the availability of processing resources. Schwartz et al. (1998) have observed that among mildly impaired patients with TBI, omission errors appeared only on the most complex tasks. Furthermore, a strong positive correlation between error rate and the proportion of errors that are omissions has been consistently reported across a range of patient populations (right stroke, Schwartz et al., 1999; left stroke, Buxbaum, Schwartz, & Montgomery, 1998; degenerative dementia, Giovannetti et al., 2002a). In sum, Schwartz and colleagues have proposed that omission errors, relative to other error types, are especially sensitive to limitations in processing resources from any source (e.g., brain damage, task demands, etc.). We assumed that participants would require fewer resources to perform the CC with practice. Thus, our third prediction was that the proportion of omissions (omission proportion) would be lower in late practice than in early practice.

If well-practiced performance relies more strongly on an action plan and requires fewer processing resources, then there is reason to expect that practice will affect error detection. Two broad classes of action errors have been described in the literature: mistakes and slips. The former are failures in problem solving or forming intentions/plans; these errors are committed by novices who lack a well-specified action plan or schema. The latter are actions not as intended (Norman, 1981; Reason, 1979) and occur on familiar tasks for which there are clear plans/schemas. Although slips are often detected, mistakes often go undetected because there is no mismatch between the action and the intention (Reason, 1990). Furthermore, classic models of error monitoring propose that sufficient processing resources are necessary to detect the mismatch between actions and intentions that occur in slips. Therefore, we hypothesized that error detection would improve with practice as the action plan was strengthened and greater processing resources were available for monitoring. Our fourth prediction was that the proportion of errors that are detected would increase in late practice relative to early practice trials.

Finally, to elucidate the manner in which participants learned the CC task, we examined the sequence of task steps performed across the practice trials. We purposefully instructed participants to perform the CC steps in any order they wished, because we wanted participants to deliberate over the serial order rather than simply memorizing or mimicking a sequence of steps. However, we were interested in learning whether or not participants performed the CC in the same serial order across the practice trials (e.g., add cream → add sugar → stir). We suspected that participants would come to perform the task in a rigid sequence across practice trials, as this strategy would minimize memory demands over time and facilitate proceduralization of the task. There is an alternative possibility: Because the placement of objects differed on each trial, we also reasoned that as participants developed expertise with the task, they might begin to perform the CC steps in a more inconsistent fashion in attempt to minimize time (e.g., selecting objects on the basis of their location on the tabletop). The prediction here is that as knowledge of the task and action plan was strengthened with practice, participants would demonstrate increased flexibility with the task. We examined differences in the consistency of serial ordering between late and early practice trials. We also explored the relation between the consistency of the task sequence and CC performance to determine whether a fixed or a flexible serial-order "strategy" was more advantageous.

In sum, in addition to improved speed and accuracy, we predicted qualitative changes in performance, including the anticipatory practice effect, a decline in the proportion of omission errors, and greater error detection on late practice than early practice trials. Finally, the consistency of the sequence of task steps was examined between the practice phases and in relation to CC performance.

Method

Participants

A total of 17 healthy participants (M age = 35.4 years, SD = 9.3; M education = 15.1 years, SD = 2.7) were recruited through an advertisement distributed to Albert Einstein Health Care Network employees (Philadelphia, PA). All participants signed Institutional Review Board (IRB)-approved informed consent forms and received $30.00 for their participation.

Procedure

A total of 10 trials were performed in this experiment (i.e., Trials 1–5 = early practice; Trials 6–10 = late practice). On each CC trial participants were required to make two cups of coffee with creamer and sweetener, each for a different fictitious person ("Joe"—Cup 1 & "Martha"—Cup 2; see Table 1). Participants used 8 unique objects for each cup. For example, as shown in Table 1, Joe's coffee required an electric drip coffee maker, a green travel mug, artificial sweetener, fresh cream, and so on. Martha's cup required a ceramic mug, hot water pitcher and manual drip coffee filter, sugar, nondairy creamer, and so on. A total of 16 objects were used for the task. All objects were placed on a U-shaped tabletop for the duration of the trial (see Figure 1). Participants were seated at the center of the table so they could easily view and access all objects.

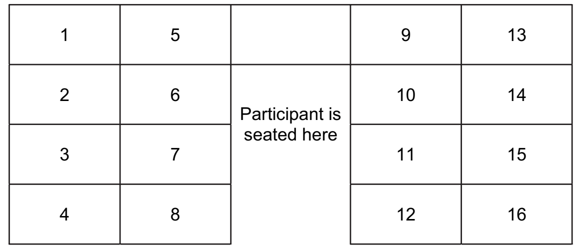

Figure 1. Schematic of Coffee Challenge table locations.

The objects and task goal remained constant, but the arrangement of objects on the tabletop differed from trial to trial. This was done to insure that participants were gaining superordinate knowledge of the task goal rather than simply developing low-level movement (e.g., reaching) plans based on the spatial location of targets. Furthermore, in an attempt to make the task more difficult, the location of an object alternated randomly with its functionally similar "token" pair in one of two mirror locations on the U-shaped table (see Figure 1). For example, the fresh cream was consistently placed in either Location 7 or Location 11 (see Figure 1), alternating with the nondairy powdered creamer. The location alternation manipulation was designed to bias participants' attention to the target and a compelling (token) distractor when searching for objects (Remington & Folk, 2001).

Prior to the first CC trial, participants were told which objects to use for Joe versus Martha's coffee. We instructed participants to avoid touching or moving objects until ready to use them. Therefore, an error was coded any time a participant touched or moved an incorrect object. Participants were also told to work as quickly as possible. The sequence of the task was not specified, but participants were encouraged to interleave the steps of the two coffee cups to maximize speed. Participants were given an opportunity to ask questions before beginning the first trial. Typically, participants asked to review which objects to use for "Joe" versus "Martha"; these instructions were repeated several times.

TABLE 1
Objects used in the Coffee Challenge

Object type	*Token 1 (Cup 1, "Joe")*	*Token 2 (Cup 2, "Martha")*
Coffee maker	Electric drip coffee maker (with glass pitcher)	Hot water pitcher
Filter holder	Basket filter	Manual drip cone filter
Filter paper	Basket filter paper	Cone filter paper
Mug	Green travel mug	White ceramic mug
Coffee	Regular coffee in can	Hazelnut coffee in bag
Sweetener	Artificial sweetener in packet	Sugar in bowl
Creamer	Fresh cream in small pitcher	Nondairy powder creamer in jar
Stirrer	Spoon	Plastic stirrer

During each CC trial, the experimenter timed participants and closely monitored their errors. After each trial, participants were provided immediate feedback on errors and total time. For example, participants were made aware of all errors (e.g., "you put the nondairy creamer in 'Martha's' cup," "you forgot to stir 'Joe's' cup," etc.) and were urged to avoid making the same error on subsequent trials. Participants were also told their completion time and were encouraged to try and beat their fastest time on each CC trial. All trials were videotaped for later analysis by one of two coders (see interrater reliability data, below).

Performance analysis

All CC variables were collected separately for early practice (Trials 1–5) and late practice (Trials 6–10). Time (in seconds) to complete the task was recorded for each trial (time to completion). An error was coded when an incorrect action was executed or when a distractor (i.e., any nontarget) object was touched or reached for, even if it was never used or lifted from the tabletop. All errors were classified according to the taxonomy listed in Table 2.

All errors were also classified as either "detected" or "undetected." A detected error was coded when a participant reached toward or touched a distractor object but stopped short of using it (i.e., microslip[2]). Errors were also coded as detected if the participant attempted (successfully or not) to correct the error at any point in the task or if the participant made a verbal comment or exclamation (e.g., "oh no!") or a predetermined set of behavioral reactions to the error, including distinctive manual and facial gestures indicating surprise or disappointment (see Hart, Giovannetti, Montgomery, & Schwartz, 1998). All other errors were coded as "undetected."

Consistency of serial order

The sequence of task steps was coded according to procedures described in Joe, Ferraro, and Schwartz (2002). First, 18 CC steps were defined (e.g., 1: place basket filter paper in basket filter holder; 2: scoop regular coffee into basket filter; 3: place basket filter holder into drip coffee maker, etc.). Second, the most frequent or "modal" route through the CC task across the 10 trials was identified for each participant. Third, for the sequence of steps that comprised the modal route, transition probabilities were computed for each adjacent pairs of steps (e.g., filter paper in basket $\rightarrow$ coffee in basket). The numerator in the transition probability fraction was the number of times "filter paper in basket" and "coffee in basket" were performed in succession at any point in the task. The denominator was the number of trials, namely 5 (transition probabilities were computed separately for early practice and late practice trials). Finally, the mean transition probability was calculated for all of the steps in the modal route (range=0 – 100). Transition probabilities at or near 100 indicated that the CC steps were performed in the same order across trials.

Data analyses

Errors were summed, and time scores were averaged separately for Trials 1–5 (early practice) and 6 – 10 (late practice) for each participant. Total

[2]Microslips are similar to "covert repairs," which have been described in the language literature as speech errors that are inhibited in time so that they do not form frank, overt errors but present as disfluencies (Hartsuiker & Kolk, 2001; Postma & Kolk, 1993).

TABLE 2
Coffee Challenge error taxonomy

General category	*Error type*	*Definition*	*Example*
Sequence	Perseveration	Object is used a second time (or more) after it had been used correctly	Sugar added to the white ceramic mug twice
	Anticipation	Object is used before completing the necessary preceding steps	Filter basket placed in coffee machine before adding coffee
	Omission	A task step is never performed	Does not add sugar to mug
Substitution		Alternate object selected in place of target object	Puts sugar (instead of artificial sweetener) into green travel mug; puts coffee (instead of sugar) into white ceramic mug
Miscellaneous	Action addition	Additional step is performed	Artificial sweetener added to white mug with sugar and nondairy creamer
	Tool omission	Step is performed without the necessary tool	Scoops sugar/coffee with hand
	Manner substitution	Incorrect gesture is used to perform a step	Fresh cream added to mug with spoon (instead of pouring from pitcher)

errors and mean time to completion were compared across the practice conditions. Because the frequency of errors was higher in early than in late practice, proportion scores were calculated for each participant and analyzed to examine qualitative changes in sequence errors and error detection (see Postma, 2000). Proportion scores for sequence errors were calculated using total sequence errors as the denominator (e.g., anticipation proportion = total anticipations/total sequence; see Dell et al., 1997). To assess changes in error detection, the proportion of total errors that were detected was calculated (detected proportion = total detected/total errors). Finally, the difference in the consistency with which CC steps were performed was examined by comparing transition probabilities for early practice versus late practice. Also, correlations were performed between transition probabilities and total errors and time to completion to assess whether or not performing the CC in a consistent sequence across trials was associated with fewer errors and faster performance. Differences across the practice conditions were assessed using paired t tests. Wilcoxon Signed Ranks Tests were performed for variables that were not normally distributed even after transformations were applied.

Interrater reliability

Two coders independently scored six representative participants to assess interrater reliability for all of the performance measures collected throughout the study.

Results

Interrater reliability

Error-coding reliability, measured as mean percentage agreement for determining whether an action was an error versus correct was 94.1% (SD = 1.1%). Of the errors detected by both coders, mean percentage agreement was 94.9% (SD = 10.0%) for classifying the errors according to the taxonomy in Table 2. Mean percentage agreement for coding an error as detected versus undetected was 85.2% (SD = 9.3%). Coding disagreements were resolved through discussion and/or review of participants' videotapes.

General error variables, time to completion, speed–accuracy analysis, and demographic variables

Consistent with our first prediction, participants were more accurate (total errors) and faster (time to completion) on late than on early practice trials (see Table 3). The effect of practice was observed for all major error types (sequence & substitution); Miscellaneous errors occurred too infrequently (i.e., n = 6; 1.3% of total errors across all practice trials) for statistical analysis.

The decrease in CC errors with practice cannot be explained by a speed–accuracy trade-off. Time to completion was significantly lower on late practice trials, and participants with higher total errors had higher time to completion averages (Pearson r = .62, p = .009). Also, there was no significant relationship between participants' age or education and total errors or time to completion (rs < .35, ps > .16 for all).

Sequence errors

The average total and proportion of sequence error types are shown in Table 4. As expected, participants committed fewer errors of each type on late practice trials.

Consistent with the *anticipatory practice effect*, the anticipation proportion was significantly higher in late practice than in early practice. Perseveration and omission proportions showed the opposite pattern of change—lower in late than in early practice; as predicted, the change was statistically reliable for only the omission proportion (see Table 4).

Error detection

Table 5 shows that total detected and total undetected errors decreased in the late practice versus

TABLE 3
General error variables and time to completion for Experiment 1

	Early practice		*Late practice*		*Analyses*	
	M	*SD*	*M*	*SD*	*t*	*p*
Total errors	17.7	9.6	10.4	6.0	4.6	<.001
Mean time to completion[a]	99.7	15.3	73.4	10.0	14.8	<.01
Total sequence	8.4	4.4	4.8	3.6	4.3	<.01
Total substitution	8.3	5.6	5.3	4.1	3.4	<.01

[a]In s.

TABLE 4
Sequence variables for Experiment 1

	Early practice		*Late practice*		*Analyses*	
	M	*SD*	*M*	*SD*	*t*	*p*
Total anticipation	7.0	4.2	4.5	3.5	3.5	<.01
Total omission	1.0	1.2	0.24	0.56	2.32[a]	<.05
Total perseveration	1.1	0.82	0.29	0.47	2.67[a]	<.01
Anticipation proportion	.751	.210	.894	.153	–2.6	<.05
Omission proportion	.116	.135	.038	.085	2.5	<.05
Perseveration proportion	.133	.128	.068	.136	1.3	*ns*

[a]Indicates Wilcoxon *z*-score value.

TABLE 5
Error detection variables for Experiment 1

	Early practice		*Late practice*		*Analyses*	
	M	*SD*	*M*	*SD*	*t*	*p*
Total undetected	3.9	3.7	1.1	2.0	3.19[a]	<.01
Total detected	13.7	7.4	9.2	10.4	2.85[a]	<.01
Detected proportion	.792	.158	.927	.106	3.02	<.01

[a]Indicates Wilcoxon *z*-score value.

early practice trials. As predicted, the mean detected proportion was significantly higher in the late practice CC.

Consistency of serial order

There was no difference in the mean transition probability for early practice trials ($M=80.6$, $SD=8.5$) versus late practice trials ($M=80.0$, $SD=12.0$; $t=0.19$, $p=.85$). Overall, transition probabilities were high, but there was considerable variability across participants (range 60.2–95.3). Of note was that some participants showed higher transition probabilities in late practice than in early practice, while others showed the opposite pattern or little difference between practice phases. In fact, early practice and late practice transition probabilities were not significantly correlated ($r=.27$, $p=.30$). In the early practice phase, transition probabilities were significantly negatively correlated with total errors ($r=-.52$, $p=.03$), but not with mean total time ($r=.16$, $p=.54$). This same pattern of correlations was observed for late practice transition probabilities (total errors, $r=-.61$, $p < .01$; total time, $r=-.30$, $p=.25$).

Discussion

All participants comprehended the CC instructions; yet, errors were committed at rates sufficient for analysis. CC performance was reliably coded, and, as predicted, error rates and completion times decreased significantly with practice (Sellen & Norman, 1992; Shallice & Burgess, 1991). CC variables were not influenced by age or education, and speed–accuracy trade-offs were observed neither in the data of individual participants nor in the group. The significant increase in the proportion of anticipation sequence errors and detected errors in late practice suggests that practice developed and strengthened a plan for behavior and reduced the resource demands necessary to complete the task. Overall, participants performed the CC steps in a relatively consistent order even early in the course of practice; however, participants who demonstrated the most consistency across trials also committed fewer errors.

This is the first study to demonstrate the anticipatory practice effect in everyday tasks (see Palmer & Drake, 2000 for similar findings in piano playing). This implies overlap (or at least similarity) between the serial-order mechanisms for language and naturalistic action (Dell et al., 1997; see Crozier et al., 1999). Moreover, according to the notion that plan-driven behavior is prone to anticipation errors, this finding shows evidence that the action plan was strengthened over practice with the CC.

As previously stated, Schwartz et al. (1998) proposed that omission errors were particularly sensitive to resource limitations among patients with neuropsychological impairment. Similarly, our results showed a link between error rates and omissions, such that the omission proportion was significantly lower in late practice when overall error rate was also low. The decline in omissions over practice is consistent with patient studies and may be due to the reduction in resources needed to execute the task, the strengthening of the action plan, or both.

The proportion of errors that were detected (i.e., slips) significantly increased on late practice trials. The high demand for processing resources on early CC trials may have precluded error detection; as participants gained practice, more resources became available for monitoring, and errors were more likely to be detected. In addition, we often observed that participants were unsure of which ingredients or mug to use for “Joe” versus “Martha” on early trials. In these situations, participants guessed (sometimes incorrectly) when selecting objects (i.e., “I’m not sure, but I think Joe wants hazelnut coffee”). Thus, participants often intended many of their early practice errors. Following additional practice and feedback from the experimenter, memory for the task was strengthened, and errors were more likely to reflect slips (actions not as intended; detected errors). Thus, increased error detection in late practice was likely due to both reduced resource demands and the development of strong and specific action plans to guide performance (see Funnell, 2001).

Finally, participants performed the CC steps in a fairly consistent order across practice trials. There was no significant difference in transition probabilities between early and late practice trials, and these probabilities were not correlated. This suggests that individual participants may have relied on different serial-order strategies to maximize their performance over the practice trials. That is, some participants performed the task in an increasingly fixed order, while others performed the task in a more flexible order, possibly ordering the task steps based on the arrangement of objects on the tabletop. Correlation analyses suggested that performing the task in the same serial order across trials was a more advantageous strategy, as participants who were more consistent made fewer errors. With the exception of Joe et al.’s (2002) study, serial-order strategy has been largely ignored in naturalistic action research; our results demonstrate that this factor may significantly influence performance variables and should be considered in future work.

In sum, the practice phase of the CC improved participants’ speed and accuracy and changed performance patterns in a manner consistent with routinized or expert behavior. In Experiment 2, we employed a divided-attention manipulation that simulated real-life multitasking in an attempt to elicit errors on the well-practiced CC task. We also examined qualitative aspects of performance to explore how the divided-attention manipulation influenced the pattern of action errors and error detection.

EXPERIMENT 2: EFFECT OF DIVIDED ATTENTION

Everyday action errors are known to increase when individuals are engaged in parallel cognitive activity (i.e., divided attention; Reason, 1979, 1984, 1990; Reason & Mycielska, 1982; Sellen & Norman, 1992; see also Manly, Lewis, Robertson, Watson, & Datta, 2002; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997). As noted earlier, numerous studies of clinical populations indicate that everyday action is resource demanding and highly sensitive to decrements in resource availability from any source (e.g., brain damage, divided attention, etc.; Schwartz et al., 1998). However, the effect of divided attention on naturalistic action has not been extensively investigated. The aim of this study was to validate a divided-attention manipulation with the CC for the study of action errors on routine tasks.

We required participants from Experiment 1 to perform the CC while simultaneously performing the Oral Trail Making Test (OTMT; see Humphreys et al., 2000). Our aim was to divert resources away from the CC, mimicking the demands of an important or interesting real-life task. The OTMT was selected for this purpose for several reasons: (a) Humphreys et al. (2000) reported success with the task; (b) it requires a verbal response so the hands and eyes are free to work on the primary, CC task; (c) it requires continuous processing and responding and sustained effort, which minimizes time off-task; and (d) it recruits a widely distributed network of cortical structures (Moll, Oliveira-Souza, Moll, Bramati, & Andreiuolo, 2002). Performance on CC-OTMT concurrent trials (concurrent-CC) was compared to a “baseline” condition with the standard CC task (standard-CC). Our first prediction was that the OTMT would divert processing resources from the CC, thereby making performance slower and more error prone in the concurrent-CC than in the standard-CC.

Assuming the divided-attention manipulation increases error rate by stealing resources or weakening the influence of the action plan, then predictions regarding qualitative changes mirror those of

Experiment 1. That is, the pattern of behavior in the concurrent-CC should revert back to novice, early practice performance. In fact, Dell et al. (1997) proposed that the anticipatory practice effect is explained parsimoniously by a fundamental association between the tendency to anticipate and overall error rate (i.e., general anticipatory effect). Dell et al. (1997) reasoned that high error rates in speech, whether from lack of practice, divided attention, time pressure, or other causes, imply a weak influence of the action plan on behavior. By contrast, when the influence of the action plan is strong, then error rates are low, and there is a tendency to anticipate future steps (anticipations). If there is a relationship between error rate and the strength of the action plan, then the proportion of anticipation errors should be lower in the concurrent-CC than in the standard-CC.

Studies of neurologically impaired patients and computer simulations of action errors (as well as the results of Experiment 1) show an association between high error rates and omission errors (Buxbaum et al., 1998; Schwartz et al., 1999; Schwartz et al., 1998; see also Cooper et al., 2005). This relationship has been demonstrated across patients (i.e., high error makers show a higher proportion of omissions than do low error makers) and within patient(s) across tasks of varying complexity (i.e., the rate of omissions increases on demanding, complex tasks relative to simpler tasks[3]). Because omission errors are especially sensitive to resource limitations (even when imposed by increased task demands) in neuropsychological populations (Schwartz et al., 1998), we predicted that the proportion of errors that are omissions would be significantly higher in the concurrent-CC than in the standard-CC.

Several theories suggest that processing resources are necessary for error detection (Goldberg & Barr, 1990; Norman, 1981; Sellen & Norman, 1992; Stuss, Shallice, Alexander, & Picton, 1995; see also Hart et al., 1998). In a study of error detection in closed head injury (CHI), Hart et al. (1998) proposed that brain damage may "de-expertize" individuals. Thus, patients must expend more processing resources on tasks that were previously performed semiautomatically "at the expense of the ability to monitor, detect and respond to errors" (p 26). Therefore, we predicted that the proportion of errors that are detected would be significantly lower in the concurrent-CC than in the standard-CC.

We considered the possibility that those participants who had not become as expert as others on the CC over practice would have weaker action plans/knowledge and would be more vulnerable to the effects of the divided-attention condition. Therefore, we examined the relation between late practice performance (e.g., total errors & time to completion) and performance on the concurrent-CC. We predicted that the correlation analyses would show that individuals with higher rates of errors and slower completion times in late practice also would demonstrate higher error rates, slower completion times, lower proportion of anticipation errors, higher proportion of omission errors, and lower proportion of detected errors in the concurrent-CC.

Finally, we examined the consistency with which participants performed the CC steps when working under divided attention. We predicted that participants would experience difficulty performing the CC according to their intended action plan, which would lead them to perform the CC steps in a less consistent order in the concurrent-CC condition than in the standard-CC condition. Based on the results of Experiment 1, we also predicted that participants who performed the CC steps in a more consistent order across trials would make fewer errors.

Method

Participants

All 17 participants from Experiment 1 returned for a second session the following day to complete Experiment 2.

Procedure

Participants were required to perform the CC under two conditions: (a) standard—the CC was performed as in practice trials; and (b) concurrent—the OTMT and CC were performed concurrently. Four blocks of 3 trials (total 12 experimental trials) were administered, alternating between the standard-CC and concurrent-CC conditions (ABAB).

All participants clearly remembered the CC task from the previous testing session. Nevertheless, prior to the first trial, participants were reminded of the task instructions, including the objects used for Joe versus Martha, that they should avoid touching/moving objects before they were ready to use them, and so on. They were also reminded of their fastest time from the previous session and were asked to work to beat that time. Unlike practice trials, feedback on errors was not provided in

[3]This is true even after error rates are standardized to account for differences in error opportunities across tasks.

Experiment 2. Performance was videotaped for later scoring by one of two coders.

Prior to the first concurrent trial, participants were instructed on the OTMT. Participants were told that the OTMT required alternating between reciting letters and numbers. An example was provided (e.g., A–1, B–2, C–3, etc.), and participants were asked to begin with a practice item (e.g., beginning with D–4). A second example was then provided (e.g., G–4) for the participants to practice and demonstrate their competence with the task. The examiner corrected all OTMT errors made during practice.

Participants were told that their performance on both the CC and OTMT would be evaluated for both speed and accuracy so that they should work quickly and without error on each task. They were also instructed to perform both tasks simultaneously (e.g., "don't start the counting, and then pause to perform steps of the coffee task"). Finally, they were told that if they were to reach the end of the alphabet, they should continue with the first letter, "A," but keep the number sequence the same (e.g., "if you get to Z–20 your next letter–number pair will be A–21, B–22, and so on."). Participants were presented with the following arbitrary letter–number pairs on consecutive concurrent-CC trials: F–7, R–2, L–11, N–23, J–10, H–4. During the concurrent trials, the experimenter monitored participants' OTMT responses. If at any point participants stopped responding or lost track of their last OTMT response, the examiner immediately provided a prompt or cue (e.g., "keep going," "you were at R15," etc.).

Performance and data analysis

The CC was scored and analyzed as in Experiment 1. For each participant, errors were summed, and time scores were averaged for the six standard and six concurrent trials.[4] Mean transition probabilities were also computed for standard and concurrent trials. The average number of seconds required to generate a correct OTMT response (i.e., a correct letter and number pair) was recorded for each participant's concurrent trials (i.e., time to completion divided by number of correct responses).

[4]Six trials were administered to generate enough error data for analyses without overburdening participants.

Results

General error variables, time to completion, speed–accuracy analyses, demographic variables, and OTMT

The concurrent task manipulation reliably disrupted performance on the well-practiced naturalistic action task. Each participant required more time and made more errors on the concurrent-CC than on the standard-CC, and the difference in time to completion and total errors was highly significant (see Table 6). Total sequence and substitutions were also significantly greater in the concurrent-CC. As in Experiment 1, miscellaneous errors occurred too infrequently for statistical analysis (i.e., $n = 6$; 1% of total errors across both conditions).

There was no evidence for a speed–accuracy trade-off. Total errors and mean time to completion were significantly positively correlated for the concurrent-CC (Pearson $r = .77$, $p < .001$) but not the standard-CC ($r = .14$, $p = .60$). As in Experiment 1, there was no significant relationship between participants' age or education and total errors or time to completion on the standard-CC or concurrent-CC (rs < .27, ps >.30 for all). There was a tendency for participants who made more errors on the concurrent -CC to require more time to generate OTMT responses (rs = .47, $p = .06$), which suggests that participants were dividing their attentional resources to both tasks, rather than prioritizing one task over the other.

Sequence errors

Participants committed more anticipations and more perseverations on concurrent-CC (see Table

TABLE 6
General error variables and time to completion for Experiment 2

	Standard-CC		*Concurrent-CC*		*Analyses*	
	M	*SD*	*M*	*SD*	*t*	*p*
Total errors	11.4	5.9	38.5	25.3	–3.62[a]	<.001
Mean time to completion[b]	66.4	9.1	93.2	19.6	–7.8	<.001
Total sequence	5.76	4.1	14.18	7.5	–4.4	<.001
Total substitution	5.65	3.64	23.9	18.8	–3.62[a]	<.001

[a]Indicates Wilcoxon z-score value. [b]In s.

TABLE 7
Sequence variables for Experiment 2

	Standard-CC		*Concurrent-CC*		*Analyses*	
	M	*SD*	*M*	*SD*	*t*	*p*
Anticipation total	4.9	3.9	9.9	5.2	3.46	<.01
Omission total	0.18	0.39	0.59	0.94	1.82[a]	*ns*
Perseveration total	0.71	0.85	3.6	3.0	3.27[a]	<.01
Anticipation proportion	.793	.276	.723	.171	1.6[a]	*ns*
Omission proportion	.056	.137	.033	.054	0.17[a]	*ns*
Perseveration proportion	.151	.175	.245	.168	1.9[a]	*ns*

[a]Indicates Wilcoxon *z*-score value.

7). Omissions also increased, but the analysis just missed significance, likely due to low omission rates in both conditions. Our predictions regarding sequence errors in the divided-attention condition were not supported. While the pattern of errors suggested a smaller anticipation proportion and a higher perseveration proportion in the concurrent-CC than in the standard-CC, the differences were not statistically significant (see Table 7). Thus, at best, there was only weak support for a general anticipatory effect. Also, contrary to prediction, there was no difference in omission proportion between the CC conditions.

Error detection

Table 8 shows a higher rate for both total detected and total undetected errors in the concurrent-CC. However, the detected proportion was not significantly different across the CC conditions. Despite the striking increase in error rate in the concurrent-CC, participants detected just over 90% of errors in both conditions.

These results were quite surprising. In order to be confident that error detection was not affected by the concurrent task, we conducted post hoc analyses on the timing of error detection across conditions. Detected errors were classified as either (a) microslips—errors caught immediately before or as the error is being committed—or (b) corrected/aware—errors detected after the error has been committed. If diverting attention has its major effect on the speed of monitoring, then we could see a trade-off between microslips and corrected/aware errors. However, as shown in Table 9, there was no difference in the microslip proportion between the CC conditions. The majority of errors were detected very quickly in both the standard-CC and the concurrent-CC.

Relations between late practice performance and concurrent-CC performance

Late practice total errors significantly correlated with concurrent-CC total errors ($r = .48$, $p < .05$),

TABLE 8
Error detection variables for Experiment 2

	Standard-CC		*Concurrent-CC*		*Analyses*	
	M	*SD*	*M*	*SD*	*z*	*p*
Total undetected	1.2	2.1	2.8	2.8	2.3	<.05
Total detected	10.4	5.5	35.6	23.3	3.6	<.001
Detected proportion	.910	.140	.933	.460	.11	*ns*

TABLE 9
Speed of error detection in Experiment 2

	Standard-CC		*Concurrent-CC*		*Analyses*	
	M	*SD*	*M*	*SD*	*z*	*p*
Total microslip	6.6	2.9	26.7	17.2	3.6	<.001
Total detected/aware	3.8	3.6	8.9	7.2	3.0	<.01
Microslip proportion	.687	.207	.752	.105	1.5	*ns*

time to completion ($r = .48$, $p < .05$), and omission proportion ($r = .51$, $p < .05$). Late practice errors were not significantly correlated with anticipation proportion ($r = -.33$, $p > .05$) nor detected proportion ($r = -.40$, $p > .05$); however, the analyses just missed significance and were in the predicted direction. That is, individuals with more errors on late practice trials had lower anticipation and detected proportion scores. Correlations between late practice time to completion and concurrent-CC total errors ($r = .69$, $p < .01$) and time to completion ($r = .84$, $p < .01$) were statistically significant. All other correlations were nonsignificant (omission proportion $r = .07$; anticipation proportion $r = -.21$; detected proportion $r = -.17$; all ps $> .05$).[5]

Consistency of serial order

Contrary to prediction, there was no significant difference in transition probabilities between the standard-CC ($M = 81.8$, $SD = 9.7$) and the concurrent-CC ($M = 79.2$, $SD = 9.7$; $t = 1.3$, $p > .05$). Standard-CC and concurrent-CC transition probabilities were significantly correlated ($r = .61$, $p < .01$). Standard-CC transition probabilities significantly correlated with standard-CC total errors ($r = -.53$, $p < .05$), but not standard-CC total time ($r = .19$, $p > .05$). Correlations between concurrent-CC transition probabilities and concurrent-CC total errors ($r = -.38$, $p > .05$) and time ($r = -.38$, $p > .05$) just missed statistical significance but were in the expected direction.

Discussion

All participants understood the concurrent-CC task instructions and exerted considerable effort to complete the CC and OTMT simultaneously. As in Experiment 1, dependent variables were not influenced by participants' age or education, and there was no evidence for a speed–accuracy trade-off in either condition. Moreover, consistent with the basic principle that naturalistic action, even when well practiced, requires attentional resources, the divided-attention manipulation had a significant effect on speed and accuracy.

The significant effect of the concurrent-CC afforded the opportunity to examine the nature of performance errors from divided attention. Overall, the results suggested that the secondary task diverted processing resources from the CC task, but there was little evidence suggesting that this manipulation significantly weakened the influence of the action plan on performance. For example, we found only weak support for the general anticipatory effect. Although the anticipation proportion was lower in the concurrent-CC, the difference was not statistically significant. It is possible that the general anticipatory effect in naturalistic action may be too small to detect with the current sample size. Alternatively, the divided-attention manipulation may have increased errors without greatly weakening the influence of the action plan.

Second, contrary to prediction, we found no evidence for a higher proportion of omission errors in the concurrent-CC. These results differ from studies of patient populations, which have shown omission to be the error type most sensitive to resource limitations (Schwartz et al., 1998). The temporary resource limitations imposed by the divided-attention manipulation may differ in degree or kind from the chronic resource limitations caused by brain damage. Brain damage may have a greater impact on arousal, which could contribute to omissions. Additionally, patient studies have not included prior practice and feedback; therefore, in some cases of moderate to severe neuropsychological impairment, omissions may have resulted from uncertainty as to the task requirements. The fact that omissions were most frequent in early practice (Experiment 1) suggests that CC omissions may have been due to limitations in recall of the task requirements.

Contrary to our prediction regarding error detection, our results suggest that in the face of a concurrent task that significantly increased performance errors, monitoring was largely unaffected. The large majority of concurrent-CC errors were detected very quickly. Findings from ERP, RT, and speech error studies indicate that in some instances error detection may be carried out without conscious awareness or control (Oomen & Postma, 2002; Postma, 2000). Furthermore, earlier work by our group has shown no meaningful relationship between error correction and error rate or overall dementia severity in patients with degenerative dementia (Giovannetti, Libon, & Hart, 2002b). Thus, while not predicted, prior studies support the possibility that error detection does not depend on the same limited capacity resources that are necessary for naturalistic action performance and that some aspects of detection may occur relatively automatically.

We acknowledge the possibility that resources may have been available for monitoring if participants shared (or rapidly switched) attention between the

[5]It is worth noting that the correlations reported here were not specific to late practice performance variables. The same pattern of correlations was observed with early practice total error and time to completion.

OTMT and CC on the concurrent-CC (see Plasher, 1994). However, in view of the fact that the OTMT occupied attention well enough to have a major impact on speed and accuracy, it is unlikely that attentional switching alone can explain the high degree of monitoring that we observed. Some combination of automatic monitoring and attention sharing/shifting does, however, appear plausible.

We suspected that participants who demonstrated higher error rates and required more time to complete the CC following the 10 practice trials in Experiment 1 had relatively weak action plans/knowledge and would be more vulnerable to the effects of the divided-attention manipulation than participants who committed fewer errors and obtained faster times. In fact, error rates and completion times on late practice trials were significantly correlated with concurrent-CC performance variables, including the proportion of sequence errors that were omissions. Correlations between late practice trials and concurrent-CC anticipation and detected proportions just missed statistical significance and were in the expected direction. Thus, participants who demonstrated less expertise with the CC following practice demonstrated higher error rates as well as evidence for greater disruption of the action plan from divided attention. Although participants, as a group, did not show strong evidence that the divided-attention manipulation weakened the action plan, some participants—namely, those with relatively weak plans to begin with—demonstrated relatively greater disruption of the action plan.

Finally, contrary to prediction, participants performed the CC steps in a relatively consistent order even when attention was divided. The significant correlation between the concurrent-CC and standard-CC transition probability suggested that following practice, participants demonstrated a favored serial-order strategy or preference (e.g., relatively flexible vs. relatively rigid) that they used for the following CC trials.[6] This serial-order strategy was not significantly disrupted by the divided-attention manipulation. As observed in Experiment 1, performing the CC in a consistent fashion across trials was an advantageous strategy, even when attention was divided. Taken together, our analyses of serial-order consistency strongly suggest that patients undergoing rehabilitation for everyday functioning should be encouraged to learn and perform tasks in a consistent serial order to minimize error.

In sum, the results of Experiment 2 demonstrate that the CC and concurrent-CC improve upon previous methods for the study of errors on familiar, everyday tasks in high-functioning individuals. Specifically, the CC includes a baseline condition and a procedure for eliciting errors on a well-practiced everyday task. In the General Discussion we compare the results from Experiment 1 and Experiment 2 and discuss the implications of these findings for the study of naturalistic action impairment in neuropsychological patient populations.

GENERAL DISCUSSION

Practice and divided attention had a clear effect on performance speed and accuracy. Practice influenced qualitative aspects of performance in a manner consistent with a shift to more plan-driven and less resource-dependent behavior. The divided-attention manipulation in Experiment 2 did not revert performance on the well-practiced CC to early-practice, novice performance patterns. Thus, contrary to prediction, the pattern of naturalistic action errors and error detection was differentially affected by inexperience versus divided attention.

As stated earlier, past studies of naturalistic action impairment have shown at least two consistent findings regarding qualitative aspects of everyday action performance in moderately to severely impaired patient populations. First, error patterns are quite similar across populations when task demands are kept constant, but omissions comprise the majority of errors and increase disproportionately on demanding tasks (Buxbaum et al., 1998; Giovannetti et al., 2002a; Schwartz et al., 1999; Schwartz et al., 1998). This observation (and others) suggested a link between action errors and general/attentional resource limitations (Schwartz et al., 1998). Second, error detection is markedly impaired relative to healthy participants (Giovannetti et al., 2002b; Hart et al., 1998). Hart et al (1998) have suggested that resource limitations may explain impaired error monitoring. Thus, according to the resource hypothesis, we expected divided attention to produce an increase in omission errors and a reduction in detected errors.

Healthy participants' behavior on the CC was most similar to that of patient populations in the early practice phase, when knowledge of the task was not well established, and performance required considerable attentional resources. However, once the action plan was firmly established through practice, qualitative aspects of performance remained relatively constant despite dramatic increases in error rate from divided attention.

[6]This conclusion was also supported by the fact that standard-CC and late practice transition probabilities were significantly correlated ($r = .57$, $p = .016$).

Specifically, omission rates remained low, and error detection was unchanged despite significant fluctuations in error rate.

Hartman and colleagues (2005) recently have proposed that diverse patient populations might demonstrate similar naturalistic action problems for very different reasons (see also Buxbaum et al., 1998). It is worth noting that Hartman and colleagues (2005) did not examine error patterns or error detection; only accomplishment scores were obtained from everyday task performance. Their conclusion was based, in part, on correlation analyses showing that accomplishment scores significantly correlated with different background tests in participants with right-hemisphere stroke than in participants with left-hemisphere stroke. Accomplishment in right-hemisphere stroke participants was associated with a multiple-step problem-solving task; in left-hemisphere stroke participants it was associated with degraded object and action knowledge (see also Rumiati, 2005). Our results do not contradict those of Hartman et al. (2005); however, they imply a slightly different conclusion. That is, detailed analysis of naturalistic action performance (e.g., error patterns, rate of error detection, etc.) may uncover distinct patterns of performance between diverse patient populations.

More specifically, our findings suggest that resource limitations may not entirely account for naturalistic action impairment, or may be qualitatively different in moderately to severely impaired patient populations than in milder patients or healthy adults. It is possible that in moderately to severely impaired patients with high omission rates and undetected errors, resources limitations interact with degraded task knowledge, such that when general processing demands are minimal, greater attention may be allocated to formulating a plan for behavior. However, when demands are high, resources are insufficient for the de novo formulation of an action plan. Consequentially, task steps are omitted, and errors go undetected. Thus, among moderately–severely impaired patients studied thus far (Buxbaum et al., 1998; Giovannetti et al., 2002a; Schwartz et al., 1999; Schwartz et al., 1998), naturalistic action impairment may be characterized as novice behavior in which the action plan is not well specified, and considerable effort is necessary to perform even relatively simple, familiar tasks. On the other hand, individuals with firm task knowledge but limited processing resources should demonstrate a pattern of performance similar to that of healthy participants operating under divided attention: high error rate, low proportion of omissions, and preserved error detection. Future studies are necessary to confirm these distinct forms of action impairment.

CONCLUSION

This paper provides evidence that the CC is a valid and reliable new method for the study of action errors in healthy or mildly impaired participants. The CC includes a training phase, baseline condition, and divided-attention condition that reliably elicits errors after practice. Thus, the CC fills an important gap in naturalistic action methodology and appears to be a promising new tool for future research. Interestingly, participants differed in their approach to the task, with some participants demonstrating a relatively rigid serial-order strategy and others a more flexible approach. Moreover, one's serial-order strategy seemed to influence performance on the CC task; therefore, this factor should be examined or controlled (i.e., through explicit instruction) in future studies. It is also worth noting that the CC offers considerable flexibility in administration to address specific research questions. For instance, a range of concurrent tasks may be employed to explore whether tasks that tap specific cognitive resources or brain regions have specific effects on action performance. Participants may be instructed to perform the CC in a specific serial order to assess the influence of specific ordering strategies on performance. Furthermore, the CC may also be adapted for unimanual administration for use with hemiparetic patients. We have validated this modification in a separate study of a patient with alien hand syndrome (Giovannetti, Buxbaum, Biran, & Chatterjee, 2005).

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