

Fine-Grain Episodic Memory Processes in Cognitive Control

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Abstract. Previous task-switching research raises a question concerning the role of episodic memory processes in cognitive control. The question is framed by the contrast between two procedures, explicit cuing and randomized runs, one of which presents a task cue perceptually on every trial and the other of which involves uncued trials. The present study compares performance across these procedures. Performance errors sensitive to errors in focusing on the correct task were higher under explicit-cuing conditions than under randomized-runs conditions, consistent with a high level of proactive interference from old task information. The results support an account in which control codes stored in episodic memory play an integral role in cognitive control, even under conditions in which all information needed for performance is perceptually available.

Keywords: episodic memory, memory processes, cognitive control, task switching

A central question in the study of cognitive control is how the system is able to respond flexibly to changing environmental constraints. This question is often studied using task-switching procedures in which there are different candidate tasks to perform on each imperative stimulus and the environment periodically presents a cue to indicate which task to perform now (Kiesel et al., 2010; Vandierendonck, Liefoghe, & Verbruggen, 2010).

One specific question raised by such procedures concerns the role of episodic memory processes. The question is framed by the contrast between the *explicit-cuing* and *randomized-runs* procedures. In the former, a task cue (randomly selected) is presented for each trial. The cue typically onsets first, often followed by a cue-stimulus interval (CSI) and then onset of the target stimulus, after which the cue and target remain displayed together. The participant applies the task signified by the cue to the imperative stimulus to make a response, after which the next trial begins with another cue. In the randomized-runs procedure, a task cue (also randomly selected) is presented at the start of a run of consecutive trials and then withdrawn, and indicates the task to perform for the full run. The cue typically offsets before the target stimulus for the first trial of the run onsets (e.g., Altmann & Gray, 2008), but the procedure can also be set up so that the first trial of a run is an explicit-cuing trial, with the cue and the imperative stimulus visible together, with some number of uncued trials coming afterwards. This is the approach taken in the experiment presented here.

The two procedures differ in terms of whether it is functionally necessary for information about the current task to be stored in episodic memory. In the randomized-runs procedure, some representation of the current task – what I refer to as a *control code* – must be stored in episodic memory to govern performance on uncued trials. (I use

the term “episodic memory” to emphasize the event-based nature of control codes, which are hypothetically encoded from each new cue presentation as described below.) In contrast, in the explicit-cuing procedure, a task is relevant for only one trial and does not need to be stored in memory. (In the alternating-runs procedure, which is also in common use, episodic memory is just one candidate source of information about the current task, so isolating the role of any one source is difficult; Altmann, 2007a.)

In previous theoretical work (Altmann & Gray, 2008), we assumed that fine-grained episodic memory processes are in fact involved in explicit-cuing performance – that control codes serve to organize the various operations involved in making a response to a stimulus, even when these operations are relatively few and not that complex. In our model, performance of a cued trial – under explicit-cuing as well as randomized-runs conditions – involves the following sequence of stages:

1. Perceptual cue encoding.
2. Control-code activation.
3. Task focusing.
4. Imperative stimulus interpretation.
5. Response selection and execution.

Two of these stages represent episodic memory processes. *Control-code activation* creates and activates a new control code. This stage is triggered every time a cue is presented, so there are many codes represented in episodic memory. However, they also all decay, starting the moment activation is complete, so the most recent code is usually the most active (modulo noise in activation levels). *Task focusing* involves retrieving the most active control code from episodic memory. Usually the retrieved code will be the most recent one, because older codes will have decayed, but sometimes an older code will be transiently

more active (due to noise in activation levels) and will therefore be retrieved instead. An intrusion like this constitutes a *task-focusing error*. Whichever control code is retrieved, the system takes the meaning represented by that code and places it in the mental focus of attention, from where it guides interpretation of the imperative stimulus. Task focusing hypothetically occurs on all trials, cued and uncued, reflecting our assumption that control information in the mental focus of attention is labile, to support cognitive flexibility.

The aim here is to assess empirically whether control-code activation and task focusing operate under explicit-cuing conditions. The larger theoretical question is whether fine-grain episodic memory processes are an integral part of cognitive control, as we assumed (Altmann & Gray, 2008), or whether they are deployed only when task information has to be stored for use later when no task cue is perceptually available. I refer to the two contrasting hypotheses in terms of an *integral* role for episodic memory versus a *conditional* role for episodic memory.

I evaluate these two hypotheses empirically by contrasting performance across explicit-cuing and randomized-runs conditions. In the experiment reported below, the primary manipulation of interest is *run length*, the number of trials governed by a particular task cue. The levels are 1, 2, 3, and 5. In all cases, the task cue is perceptually available through the first trial of the run, meaning that the Run length 1 condition corresponds exactly to explicit-cuing conditions (and I use the terms interchangeably). The cue offsets after the first trial, so Run lengths 2, 3, and 5 all involve uncued trials (1, 2, and 4 per run, respectively). The run length manipulation is between subjects, so that the system is able to adapt cue-related processing to a given run length, without danger of strategic carryover effects clouding the results (Altmann, 2004a, 2004b).

Two empirical patterns are of interest. The first and more obvious one concerns response latencies on cued trials. If cued-trial latencies are faster under explicit-cuing conditions than under randomized-runs conditions, this would suggest fewer cue-related processing stages in the former case, consistent with a conditional role for episodic memory.

The second and more complex empirical pattern involves the difference between error rates on incongruent and congruent trials and how this changes with run length. An *incongruent* trial (in the task-switching context) is one on which the correct response differs depending on the task, whereas a *congruent* trial is one on which the correct response is the same for both tasks. The difference in error rates between the two is a measure of task focusing (Altmann & Gray, 2008; Ikeda & Hasegawa, 2012; Meiran & Daichman, 2005; Steinhauser & Hubner, 2006). By hypothesis (Altmann & Gray, 2008), old control codes linger in episodic memory, causing proactive interference, but the architecture lets them decay, to keep interference from becoming catastrophic. The shorter the run length in a given condition, the less time there is for old codes to decay, so the more they will interfere with task focusing on the current trial – predicting increased task-focusing errors, and thus elevated error rates on incongruent relative

to congruent trials. If this pattern extends through Run length 1, this would imply that interference from old control codes is a factor under explicit-cuing conditions, and thus support an integral role for episodic memory.

There are two ancillary factors in the experiment. I included a within-subjects manipulation of the CSI, in part because such manipulations are more common than not, but also because CSI effects have been interpreted to suggest that explicit-cuing performance does not involve task representations stored in episodic memory (Logan & Bundesen, 2003). I also manipulated cue type (e.g., “parity” and “even odd,” both referring to the same task), but this manipulation was between participants and mainly to improve generality, so I treat these two conditions as internal replications and emphasize empirical patterns that replicate for both. (Mayr & Kliegl, 2000, discuss effects of cuing the response mapping with a cue such as “even odd.”)

Method

Participants

Four hundred Michigan State University undergraduates participated in exchange for partial credit toward a course requirement. An additional 40 were replaced because their average accuracy for the experimental session was below a block-level threshold (see Procedure section). Replacements were evenly distributed across the 8 groups (6 replacements in each of four groups, and 2, 3, 4, and 7 replacements in one group each).

Materials

Cue type (one word, two words) varied between participants. The one-word cues were “parity” and “magnitude” and the two-word cues were “even odd” and “high low.” For two-word cues, the order of the two words in each cue was spatially congruent with the left-right position of the response keys. On each cued trial the cue was selected randomly within cue type. The imperative stimulus was one of the digits 1–9 except 5. On each cued and uncued trial, the imperative stimulus was selected randomly with the constraint that repetitions between trials were not allowed.

Cues and stimuli were presented in white against a black background in all-lowercase Monaco font. Characters were 5 mm tall, from baseline to *x*-height. The imperative stimulus appeared below the cue, separated by about 5 mm of blank space. Viewing distance was about 60 cm, so this separation subtended about 1 degree of visual angle, from center of cue to center of stimulus. Cue and stimulus were horizontally centered and the ensemble was vertically centered.

On each trial, the participant responded with one of two key-presses (“Z” or “/” on a QWERTY keyboard) to signify whether the stimulus was even or odd or higher or

Table 1. Response latencies from all cells of the design, for cued and uncued trials

			One-word cues					Two-word cues				
			Cue-stimulus interval (ms)					Cue-stimulus interval (ms)				
			100	300	500	700	900	100	300	500	700	900
			Run length 1									
Cued	Inc	S	951	846	775	717	693	943	811	727	695	670
		R	758	653	625	614	608	779	684	642	620	607
	Con	S	881	762	676	666	637	885	733	660	613	608
		R	704	616	581	575	569	732	626	591	568	574
			Run length 2									
Cued	Inc	S	1053	892	799	781	766	1184	1017	917	872	839
		R	847	728	690	687	672	975	862	785	761	756
	Con	S	1016	852	734	719	698	1118	970	835	796	772
		R	794	657	640	635	619	970	803	729	731	714
Uncued	Inc	S	518	509	506	507	502	536	534	524	533	520
		R	503	499	504	499	502	529	522	524	525	527
	Con	S	510	498	498	493	490	522	523	518	520	521
		R	496	489	489	493	488	518	515	512	515	517
			Run length 3									
Cued	Inc	S	1119	966	864	840	819	1124	959	858	820	790
		R	977	872	810	753	755	977	872	810	753	755
	Con	S	1075	941	811	763	750	1065	883	798	747	759
		R	942	785	752	737	690	993	816	746	731	707
Uncued	Inc	S	553	548	539	544	540	531	532	529	527	524
		R	540	548	543	535	542	525	524	525	522	527
	Con	S	540	537	539	532	530	516	519	515	511	509
		R	532	534	533	529	525	520	511	514	513	511
			Run length 5									
Cued	Inc	S	1132	1012	920	793	832	1201	1039	929	863	858
		R	1029	885	836	793	750	1090	925	865	816	826
	Con	S	1121	946	830	814	757	1137	965	871	840	832
		R	971	810	763	752	708	1042	910	828	796	798
Uncued	Inc	S	567	559	561	558	562	546	547	544	542	544
		R	560	563	563	565	561	551	549	548	544	548
	Con	S	551	548	547	549	545	538	539	536	534	534
		R	550	553	547	553	547	542	538	542	536	533

Note. Inc = incongruent, Con = congruent, S = switch, R = repeat.

lower than 5 (as required by the current task). The mapping of response categories to keys was randomized between participants. Labels indicating the response mapping were visible at the bottom left and right sides of the computer screen throughout the session.

Procedure

Participants performed a practice block with the experimenter present to answer questions, then performed 24 experimental blocks on their own. Each experimental block involved a series of *runs*, a run being a consecutive sequence of trials between cue presentations. There were 54, 42, 30, and 24 runs per block for Run lengths 1, 2, 3, and 5, respectively. The number of runs per block was chosen to roughly equate the time per experimental session across run length conditions, which was about 40 min.

After a block, the participant was given their accuracy for that block. If this was 100%, they received a message asking them to try to go a little faster. If it was less than 90%, they were asked to be more accurate (meaning that those whose session-level accuracy was less than 90% were not performing according to task requirements, and so were replaced). Participants started the next block after a self-paced rest period.

A cued trial began with a 500 ms response-cue interval (RCI), triggered by the response to the previous trial, during which the screen was blank. The cue then onset, followed by a variable CSI before onset of the target stimulus. The CSI was one of 100, 300, 500, 700, or 900 ms, randomly selected. The cue and the target remained visible together until the participant responded. For Run length 1, this response triggered the next RCI. For longer run lengths, this response triggered the first uncued trial, and the last uncued trial of the run triggered the next RCI. Between uncued trials, one response triggered immediate onset of the next

Table 2. Error percentages from all cells of the design, for cued and uncued trials

			One-word cues					Two-word cues					
			Cue-stimulus interval (ms)					Cue-stimulus interval (ms)					
			100	300	500	700	900	100	300	500	700	900	
			Run length 1										
Cued	Inc	S	9.11	8.35	7.78	7.99	6.73	7.40	5.86	5.93	5.82	4.61	
		R	5.09	5.26	5.86	5.27	5.01	3.93	5.07	4.44	4.34	4.24	
	Con	S	1.85	2.07	1.49	1.61	1.40	1.59	2.08	1.38	1.38	1.28	
		R	1.64	1.16	1.94	1.13	1.94	1.51	1.78	1.26	1.95	2.04	
			Run length 2										
Cued	Inc	S	4.86	3.96	4.41	4.19	3.34	4.48	3.69	4.29	4.39	3.92	
		R	3.02	2.62	3.32	2.86	2.46	1.53	2.21	2.14	2.37	1.80	
	Con	S	0.94	0.97	0.86	0.53	0.98	1.65	1.28	1.06	1.23	1.34	
		R	1.12	0.43	1.01	0.66	0.78	1.13	1.31	1.10	0.95	1.01	
Uncued	Inc	S	6.71	5.34	6.11	4.79	6.01	5.61	5.88	6.61	5.72	5.34	
		R	6.63	6.17	5.47	4.73	5.11	5.34	5.51	5.10	5.42	5.31	
	Con	S	2.33	3.17	2.65	3.06	2.38	3.07	4.07	3.20	3.51	3.42	
		R	3.82	3.51	3.42	3.33	3.59	4.38	4.76	3.66	4.19	3.27	
			Run length 3										
Cued	Inc	S	4.29	4.05	4.14	4.08	3.63	3.64	4.13	4.31	4.25	3.67	
		R	2.76	3.31	2.37	2.46	2.29	2.04	2.30	1.83	2.23	1.84	
	Con	S	1.18	1.03	0.80	1.37	0.86	1.15	0.94	1.17	1.02	1.24	
		R	0.59	1.34	0.71	0.87	0.84	0.44	1.01	0.79	0.77	0.85	
Uncued	Inc	S	4.44	4.46	4.27	4.29	3.89	5.54	5.15	4.65	4.94	4.48	
		R	4.31	4.36	3.69	3.78	3.48	3.39	4.36	3.48	4.53	3.48	
	Con	S	2.37	2.47	2.12	2.06	2.46	2.29	2.27	2.01	2.12	2.62	
		R	2.83	2.37	2.93	2.36	2.48	2.43	2.79	2.74	2.28	2.20	
			Run length 5										
Cued	Inc	S	4.41	5.58	5.86	4.85	4.72	4.35	4.40	2.61	2.95	3.36	
		R	2.80	3.29	3.42	3.75	3.02	3.02	2.21	1.88	1.61	1.56	
	Con	S	1.24	1.39	1.46	1.23	0.97	0.74	1.09	1.06	0.96	0.66	
		R	1.49	1.17	1.61	1.03	1.08	0.83	0.87	0.66	1.15	0.81	
Uncued	Inc	S	5.11	4.93	5.12	4.71	5.39	4.23	4.25	4.07	4.21	4.74	
		R	4.57	4.67	4.70	4.37	4.36	4.02	3.96	3.71	3.92	4.05	
	Con	S	2.65	2.72	2.71	2.73	2.84	2.00	2.20	2.03	1.87	2.33	
		R	3.00	2.76	2.83	2.76	2.89	2.19	2.49	2.28	2.25	2.36	

Note. Inc = incongruent, Con = congruent, S = switch, R = repeat.

stimulus. No accuracy feedback was given after individual trials.

The *switching* factor, with levels switch and repeat, was defined at the run level. If the cue for the current run indicated the same task as the cue for the previous run, the current run was a repeat run. If the cue for the current run indicated the other task, the current run was a switch run. A repeat trial is a trial occurring in repeat run, and a switch trial is a trial occurring in a switch run. This run-based definition reduces to the usual definition of the switching factor under explicit-cuing conditions.

Design and Analysis

The complete design was 2 (Cue type: one word, two word) \times 4 (Run length: 1, 2, 3, or 5) \times 2 (Congruency: incongruent, congruent) \times 2 (Switching: repeat, switch) \times 5

(CSI: 100, 300, 500, 700, or 900 ms). The cue type and run length factors were between participants, with 50 participants per cell. The remaining factors were within participants. An additional, unbalanced factor was whether a trial was *cued* or *uncued*, with cued trials occurring in all run length conditions and uncued trials occurring only with Run lengths 2, 3, and 5.

The cue type factor was not of theoretical interest, so I omit it from analyses of variance (ANOVAs), yielding essentially two experiments with different cue types. I perform parallel analyses on each and take as systematic those patterns that replicate for both.

The practice block and the first run of each experimental block were excluded from analysis (the first run because the switching factor was undefined). Error trials were excluded from analysis of response latencies. Response latencies were trimmed by taking the median value for each participant for each cell of the design.

Table 3. Results of 4 (Run length, cued trials: 1, 2, 3, 5) and 3 (Run length, uncued trials: 2, 3, 5) \times 2 (Congruency: incongruent, congruent) \times 2 (Switching: repeat, switch) \times 5 (Cue-stimulus interval: 100, 300, 500, 700, or 900 ms) ANOVAs for response latencies

Contrast	<i>df</i>	One-word cues			Two-word cues			
		<i>F</i>	<i>p</i>	η_p^2	<i>F</i>	<i>p</i>	η_p^2	
Cued trials								
Run length (R)	3	196	13.3	.000	.169	18.8	.000	.223
Congruency (C)	1	196	180.3	.000	.479	251.1	.000	.562
Switching (S)	1	196	250.0	.000	.561	246.4	.000	.557
Cue-stimulus interval (I)	4	784	551.1	.000	.738	954.9	.000	.830
R \times C	3	196	0.1	.952	.002	1.7	.171	.025
R \times S	3	196	3.6	.015	.052	7.1	.000	.098
R \times I	12	784	5.0	.000	.071	4.9	.000	.069
C \times S	1	196	0.3	.567	.002	19.9	.000	.092
C \times I	4	784	2.7	.029	.014	1.5	.202	.008
S \times I	4	784	44.1	.000	.184	33.6	.000	.146
R \times C \times S	3	196	1.7	.169	.025	0.2	.902	.003
R \times C \times I	12	784	1.1	.381	.016	1.0	.475	.015
R \times S \times I	12	784	1.1	.327	.017	1.3	.231	.019
C \times S \times I	4	784	1.3	.268	.007	0.4	.807	.002
R \times C \times S \times I	12	784	1.6	.087	.024	0.9	.593	.013
Uncued trials								
Run length	2	147	11.8	.000	.138	1.7	.194	.022
Congruency	1	147	62.2	.000	.297	49.6	.000	.252
Switching	1	147	9.4	.003	.060	1.1	.302	.007
Cue-stimulus interval	4	588	9.2	.000	.059	4.6	.001	.031
R \times C	2	147	0.4	.703	.005	0.6	.530	.009
R \times S	2	147	5.5	.005	.069	3.1	.048	.040
R \times I	8	588	2.0	.046	.026	0.9	.549	.012
C \times S	1	147	0.1	.815	.000	0.1	.793	.000
C \times I	4	588	0.9	.459	.006	0.1	.970	.001
S \times I	4	588	4.3	.002	.028	1.9	.102	.013
R \times C \times S	2	147	0.4	.678	.005	1.2	.295	.016
R \times C \times I	8	588	0.8	.594	.011	1.1	.333	.015
R \times S \times I	8	588	0.8	.623	.010	0.6	.761	.008
C \times S \times I	4	588	1.7	.140	.012	1.5	.205	.010
R \times C \times S \times I	8	588	0.6	.788	.008	0.5	.868	.007

Note. Bold = $p < .05$, italicized = $.05 < p < .10$.

Results

Tables 1 and 2 give response latencies and errors, respectively, separated by all factors of the full design. Table 3 gives omnibus ANOVAs for latencies on cued and uncued trials, and Table 4 gives corresponding ANOVAs for errors. I report additional statistics in the narrative below, as needed to follow up particular contrasts.

The first empirical pattern of interest is the effect of run length on cued-trial latencies, plotted in Figure 1 (solid ink). The main effect of run length was significant for both cue types (Table 3). Orthogonal Helmert contrasts showed that Run length 1 differed from longer run lengths, $F(1, 196) = 26.7, p < .001, \eta_p^2 = .026$, for one-word cues, $F(1, 196) = 51.2, p < .001, \eta_p^2 = .035$, for two-word cues; that Run length 2 differed from longer run lengths for one-word cues, $F(1, 196) = 12.7, p < .001, \eta_p^2 = .018$, but not

for two-word cues, $F < 1$; and that Run length 3 did not differ from Run length 4 for one-word cues, $F < 1$, but did for two-word cues, $F(1, 196) = 26.6, p < .001, \eta_p^2 = .026$. Thus, cued-trial latencies were faster under explicit-cuing conditions than under randomized-runs conditions, consistent with a conditional role for episodic memory. Within randomized-runs conditions, there were no differences that replicated for both cue types.

Under randomized-runs conditions one can directly estimate the time spent on cue-related processing, by comparing cued and uncued trials. In Figure 1, the trends for uncued trials across run lengths are roughly parallel to those for cued trials, and in fact difference scores formed by subtracting uncued-trial latencies from cued-trial latencies were not affected by run length, $F < 1$ for both cue types. Thus, factoring in the information from uncued trials reduces some of the noise in the Helmert contrasts above,

Table 4. Results of 4 (Run length, cued trials: 1, 2, 3, 5) and 3 (Run length, uncued trials: 2, 3, 5) \times 2 (Congruency: incongruent, congruent) \times 2 (Switching: repeat, switch) \times 5 (Cue-stimulus interval: 100, 300, 500, 700, or 900 ms) ANOVAs for error rates

Contrast	<i>df</i>	One-word cues			Two-word cues			
		<i>F</i>	<i>p</i>	η_p^2	<i>F</i>	<i>p</i>	η_p^2	
Cued trials								
Run length (R)	3	196	13.5	.000	.171	10.8	.000	.142
Congruency (C)	1	196	384.4	.000	.662	312.8	.000	.615
Switching (S)	1	196	99.2	.000	.336	71.4	.000	.267
Cue-stimulus interval (I)	4	784	3.6	.007	.018	3.4	.010	.017
R \times C	3	196	13.2	.000	.169	9.0	.000	.121
R \times S	3	196	2.9	.037	.042	1.3	.263	.020
R \times I	12	784	1.1	.335	.017	1.2	.295	.018
C \times S	1	196	90.1	.000	.315	70.2	.000	.264
C \times I	4	784	1.9	.101	.010	2.2	.065	.011
S \times I	4	784	1.5	.204	.008	2.0	.086	.010
R \times C \times S	3	196	3.1	.028	.045	0.3	.858	.004
R \times C \times I	12	784	0.8	.650	.012	1.9	.032	.028
R \times S \times I	12	784	1.6	.092	.024	1.8	.041	.027
C \times S \times I	4	784	0.8	.549	.004	0.5	.740	.003
R \times C \times S \times I	12	784	0.5	.920	.007	1.4	.174	.021
Uncued trials								
Run length	2	147	3.9	.022	.051	9.1	.000	.111
Congruency	1	147	176.2	.000	.545	127.9	.000	.465
Switching	1	147	0.1	.712	.001	2.2	.144	.014
Cue-stimulus interval	4	588	3.5	.008	.023	1.7	.159	.011
R \times C	2	147	3.0	.053	.053	0.1	.897	.001
R \times S	2	147	3.1	.050	.040	2.0	.139	.026
R \times I	8	588	0.9	.519	.012	0.9	.551	.012
C \times S	1	147	17.0	.000	.104	28.1	.000	.160
C \times I	4	588	2.1	.075	.014	0.4	.830	.003
S \times I	4	588	0.7	.570	.005	0.8	.533	.005
R \times C \times S	2	147	0.4	.668	.005	1.3	.277	.017
R \times C \times I	8	588	2.0	.043	.027	1.3	.262	.017
R \times S \times I	8	588	0.2	.981	.003	1.0	.442	.013
C \times S \times I	4	588	1.9	.107	.013	1.5	.207	.010
R \times C \times S \times I	8	588	0.7	.695	.009	0.7	.707	.009

Note. Bold = $p < .05$, italicized = $.05 < p < .10$.

and suggests that there is no evidence at all that cue-processing times (under randomized-runs conditions) were affected by run length. Altmann and Gray (2008) reported the same result from a comparison of longer run lengths. These null effects reinforce the interpretation that cue-processing time differs only as a function of whether or not task information needs to be stored in memory for use on trial(s) on which there is no cue.

The second empirical pattern of interest is the effect of run length on the difference between incongruent cued trials and congruent cued trials. Error rates on cued trials are plotted in the top panel of Figure 2. The Run Length \times Congruency interaction was highly significant for both cue types (Table 4, R \times C), with the difference between incongruent and congruent trials greatest for Run length 1. However, congruent error rates were also slightly elevated for Run length 1, so I computed difference scores by subtracting congruent from incongruent trials for each

participant for all the remaining cells of the design. Difference score means are plotted in the bottom panel of Figure 2. The effect of run length was again significant, $F(3, 196) = 13.2$, $p < .001$, $\eta_p^2 = .169$, for one-word cues, $F(3, 196) = 9.0$, $p < .001$, $\eta_p^2 = .121$ for two-word cues. Orthogonal Helmert contrasts on these difference scores showed that Run length 1 differed from longer run lengths, $F(1, 196) = 38.5$, $p < .001$, $\eta_p^2 = .031$, for one-word cues, $F(1, 196) = 26.6$, $p < .001$, $\eta_p^2 = .026$, for two-word cues; that Run length 2 did not differ from longer run lengths for either cue type, $F_s < 1$; and that Run length 3 did not differ from Run length 4 for either cue type, $F(1, 196) = 1.3$, $p = .264$, $\eta_p^2 = .006$, for one-word cues, $F < 1$ for two-word cues. These results are consistent with an integral role for episodic memory in cognitive control. The difference between incongruent and congruent trials was greatest under explicit-cuing conditions, consistent with the idea that under these conditions old control codes had the least

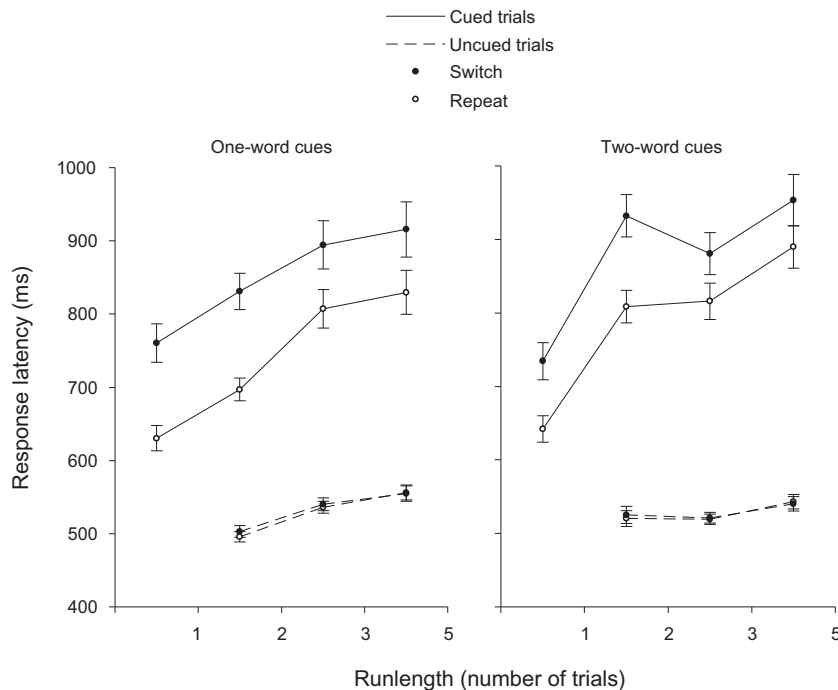


Figure 1. Response latencies on cued and uncued trials. Error bars are standard error of the mean.

time to decay and thus maximally intruded on task focusing. Note that these error results and the latency results from earlier point in opposite theoretical directions.

Finally, from Figure 1 it appears that on cued trials there was a latency switch cost for the longest runs, and although the Run Length \times Switching interaction was significant (Table 3, $R \times S$), latency switch costs were still significant at Run length 5, $F(1, 49) = 38.5$, $p < .001$, $\eta_p^2 = .440$, for one-word cues, $F(1, 49) = 29.4$, $p < .001$, $\eta_p^2 = .375$, for two-word cues. If latency switch cost on cued trials is caused by repetition priming, as two existing models contend (Altmann & Gray, 2008; Logan & Bundesen, 2003), then the substantial latency switch cost at long run lengths suggests that the source of repetition priming is mostly the previous control code (Altmann & Gray, 2008) rather than the previous cue percept (Logan & Bundesen, 2003). The $CSI \times$ Switching interaction has also been taken as evidence of repetition priming from the previous cue percept (Logan & Bundesen, 2003), and was highly significant here (Table 3, $S \times I$), but was not further modulated by run length (Table 3, $R \times S \times I$), suggesting again that repetition priming comes mainly from a control code stored in memory.

General Discussion

The question of interest was whether or not episodic memory processes are involved in explicit-cuing performance, that is, under conditions in which every trial is cued such

that task information does not strictly need to be stored in memory for use on later trials. The latency data suggest that episodic memory processes are *not* involved. Cued-trial latencies were faster under explicit-cuing conditions than under randomized-runs conditions and did not differ systematically within randomized-runs conditions (Figure 1), consistent with fewer processing stages under explicit-cuing conditions. The error evidence, in contrast, suggests that episodic memory processes *are* involved. The difference between error rates on incongruent and congruent trials, which measures error rates in task focusing, was greatest when run length was shortest (Figure 2), that is, under conditions in which old control codes were hypothetically most likely to intrude on task focusing.

The overall data pattern suggests a speed-accuracy tradeoff, with decreased response latencies and increased error rates under explicit-cuing conditions compared with randomized-runs conditions. However, to explain the Run length \times Congruency interaction for errors (Figure 2), the locus of the tradeoff would have to be task focusing. Conceivably, if less time were spent activating the control code under explicit-cuing conditions than under randomized-runs conditions, then the code would be less active and potentially less accessible to task focusing. Alternatively, and not necessarily exclusively, if less time were spent on task focusing under explicit-cuing conditions, perhaps due to a lower retrieval threshold (Altmann & Gray, 2008), the rate of intrusions from old control codes would increase. Whether and in what combination these mechanisms could account for the data is a question that would need to be answered by simulating them, which is a project well

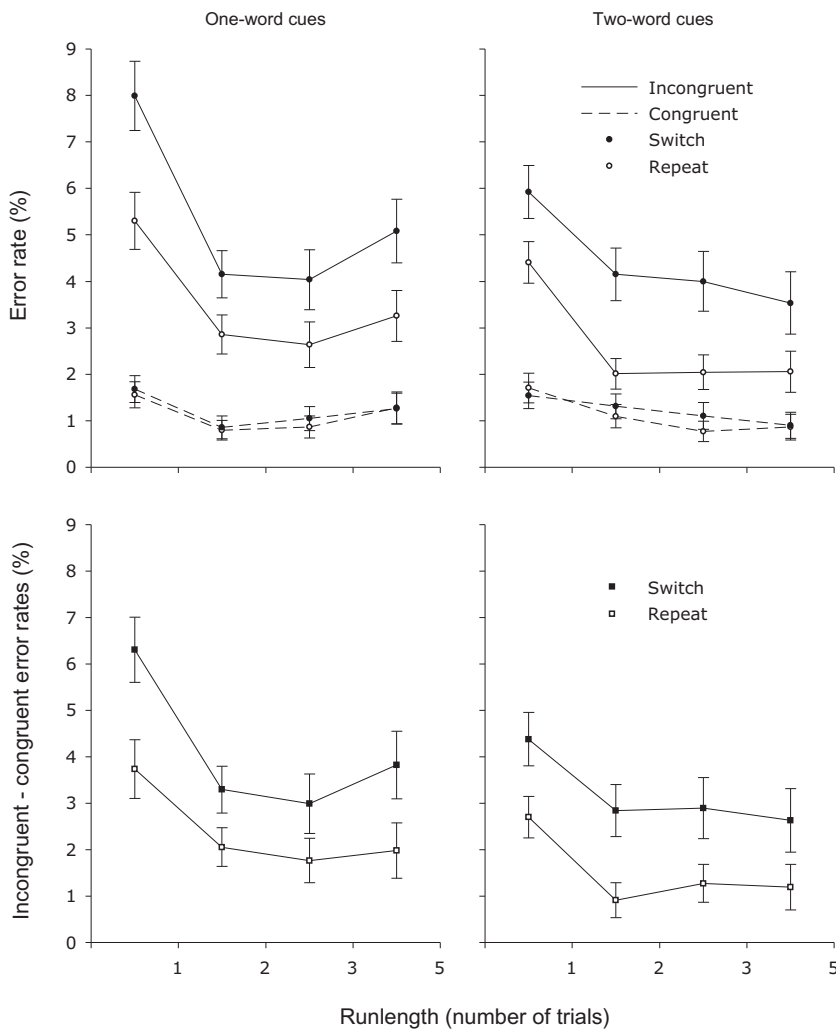


Figure 2. Error percentages on cued trials (top panels) and incongruent-congruent difference scores (bottom panels). Error bars are standard error of the mean.

beyond the scope of this study. Nonetheless, the larger issue is that even if the data reflect a speed-accuracy tradeoff, the Run length \times Congruency interaction for errors seems to implicate task focusing, and thus an integral role for episodic memory in explicit-cuing performance.

An alternative explanation for the latency results is in terms of preparatory eye movements to the location of the task cue. As in most if not all previous explicit-cuing studies, the cue and stimulus here were spatially separated, by about 1 degree of visual angle, center to center. This separation may have been enough to generate saccades from one location to the other. Under explicit-cuing conditions, with a cue on every trial, the saccade from stimulus location to cue location could have been entrained to the trial response, with the response being the trigger for the saccade. Under randomized-runs conditions this simple contingency was not available, because multiple trials requiring responses were presented in succession without

intervening cues, all requiring fixation only on the stimulus. A counting strategy to identify the last trial of a run would probably have cost more for its counting operations than the time saved by a preparatory eye movement at the end, and there was no other visual feature that onset during the RCI that could have triggered a saccade externally. The time saved by a preparatory eye movement would have been about 300 ms at maximum, which is roughly the difference in cued-trial latencies across explicit-cuing and randomized-runs conditions (Figure 1).

This explanation of the latency data would tip the balance of the present evidence sharply toward an integral role for episodic memory in cognitive – a role also supported by evidence from other lines of work. One such line involves the episodic retrieval construct (Hommel, Musseler, Aschersleben, & Prinz, 2001; Neill, 1997), which turns out to account nicely for response repetition effects in explicit-cuing performance (Altmann, 2011). The basic

idea is that response (and stimulus) repetition effects are driven by feature-level matches and mismatches between the processing context on the current trial and an episodic trace encoded from the processing context on the previous trial and retrieved on the current trial. The implication, again, is that, under explicit-cuing conditions, an episodic memory encoded on one trial affects performance on the next.

A different line of evidence involves task-switching studies in which cues are mapped 2:1 to tasks. This mapping introduces an additional level of switching, namely trials on which the cue switches but the task does not. Logan and Bundesen (2003) presented evidence of a null difference in latencies on cue-switch versus task-switch trials, interpreting this to mean that there were no task representations (separate from cue representations) involved in explicit-cuing performance. However, studies from other laboratories have generally found that cue-switch latencies are significantly faster than task-switching latencies (e.g., Altmann, 2011; Monsell & Mizon, 2006), and that on other measures, including errors (e.g., Altmann, 2006, 2011; Horoufchin, Philipp, & Koch, 2011; Mayr & Kliegl, 2003; Monsell & Mizon, 2006) and lag-2 repetition cost (Altmann, 2007b; Gade & Koch, 2008), cue-switch trials behave like no-switch trials and unlike task-switch trials. Thus, the bulk of the evidence from studies with 2:1 cue-task mappings generally supports the existence of task representations that are independent of the perceptual cues that signify them – which is another way to characterize a control code. All but two of the experiments cited above (Altmann, 2006, 2007b) used explicit-cuing procedures, suggesting that cue-independent task representations are involved even when a cue is perceptually available on every trial.¹

In conclusion, the latency data presented here support a conditional role for episodic memory in cognitive control, but could also be an artifact of eye movements under conditions in which they were easy to anticipate. The error data, in contrast, support an integral role for episodic memory in cognitive control, converging with evidence from the episodic retrieval literature and with evidence that explicit-cuing performance involves cue-independent task representations. The implications are potentially far reaching, suggesting that any kind of performance involving conditional interpretation of stimuli leaves behind a fine-grained episodic history that is available to inform and/or interfere with performance in the future.

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¹ Studies have asked whether cue-related processes change when redundant cues are added to the materials to form 2:1 cue-task mappings (Altmann, 2006; Kleinsorge, 2012). The answer seems to be “yes” – even Schneider and Logan (2011) found that across their experiments task-switch cost was significantly higher with a 2:1 mapping than with the standard 1:1 mapping. The mechanisms of these mapping effects are not yet well understood, but it is worth keeping in mind that when we modify our procedures to measure particular processes, we may also be modifying the processes.

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