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Secondary-task effects on classification learning

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Probabilistic classification learning can be supported by implicit knowledge of cue–response associations. We investigated whether forming these associations depends on attention by assessing the effect of performing a secondary task on learning in the probabilistic classification task (PCT). Experiment 1 showed that concurrent task performance significantly interfered with performance of the PCT. Experiment 2 showed that this interference did not prevent learning from occurring. On the other hand, the secondary task did disrupt acquisition of explicit knowledge about cue–outcome associations. These results show that concurrent task performance can have different effects on implicit and explicit knowledge acquired within the same task and also underscore the importance of considering effects on learning and performance separately.

A substantial body of research has shown that skill acquisition does not necessarily depend on explicit learning. Studies of patients with neurological disorders (N. J. Cohen & Squire, 1980; Gabrieli, Corkin, Mickel, & Growdon, 1993; Knowlton, Mangels, & Squire 1996), as well as neuroimaging studies of healthy populations, suggest a distinction between the neural bases of skill learning and explicit learning (Grafton, Hazeltine, & Ivry, 1995; Poldrack, Prabhakaran, Seger, & Gabrieli, 1999; Reber, Gitelman, Parrish, & Mesulam, 2003).

In addition to depending on different neural systems, skill learning and explicit learning also appear to differ in terms of sensitivity to distraction by a secondary task. Performance of a secondary task during explicit memory encoding has a consistently detrimental effect on later memory for the studied information when tested using direct tests (Craik, Govoni, Naveh-Benjamin, & Anderson, 1996). With regard to skill acquisition, there are mixed findings regarding the effects of secondary tasks on learning, which have been most extensively studied using a serial reaction time (SRT) task. For example, some studies of motor sequence learning in which an SRT task has been used have shown disruption of sequence learning (Shanks & Channon, 2002). However, dual-task interference effects appear to differ depending on the nature of the sequence (A. Cohen, Ivry, & Keele, 1990) and the timing of the secondary task (Hsiao & Reber, 2001).

Dual-task interference has been shown to disrupt learning particularly when sequence structure is ambiguous—that is, when learning cannot rely on first-order transitions between elements. In ambiguous sequences, each element is followed equally often by each other element in the sequence, necessitating higher order learning. Learning of ambiguous sequences is impaired by divided-attention manipulations, which has led to the suggestion that separate attentional and nonattentional sequence-learning mechanisms exist (Curran & Keele, 1993). However, other studies have reported that the learning of nonambiguous sequences can be strongly affected by the performance of a concurrent task (Heuer & Schmidtke, 1996). Timing of interference matters, with interference occurring later in the interval between a response and the subsequent sequence element being more disruptive than interference occurring earlier in this interval (Hsiao & Reber, 2001). Another factor that appears to be important is the degree to which explicit knowledge contributes to performance. Dual-task conditions appear to disrupt SRT performance more under conditions in which explicit knowledge of the sequence is gained. For example, the learning of a probabilistic sequence is much less affected by performing a concurrent task than is the learning of a deterministic sequence, which is more likely to be accompanied by explicit knowledge of the sequence (Jimenez & Vazquez, 2005).

One complication in the study of dual-task effects on skill learning is that a secondary task may exert its effects on acquisition and/or expression of the skill. It has previously been argued that whereas awareness of what is learned may not be necessary, all SRT learning does require attention (Nissen & Bullemer, 1987). However, evidence for a dissociation of learning and performance has also been found using the SRT. Whereas subjects may show longer reaction times (RTs) when performing the SRT under dual-task conditions, acquisition of the sequence may not be affected, as is shown by a decrease in RT under single-task conditions comparable to that for subjects trained without the concurrent task. For example, Frensch, Lin, and Buchner (1998) found that only expression, and not learning, of an SRT task was affected by a secondary task. Another example of dissociation between acquisition and expression was found in motor skill learning using a pursuit rotor task (Eysenck & Thompson, 1966). In this study, the effects of varying levels of distraction on learning and performance were assessed in separate groups. The effect on performance was commensurate with the level of dis-

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traction, whereas learning was identical in all the groups. Because skill knowledge is assessed as subjects continue to practice the skill, it may be unclear whether the addition of a secondary task impairs the amount of acquired skill knowledge or the ability to produce the skill during practice. Thus, it is important that skill knowledge acquired under dual-task conditions should be assessed in the absence of the secondary task in order to assess the role of attention in skill acquisition (Curran & Keele, 1993).

In the present study, we examined the effects of a concurrent working memory load on learning and performance of a probabilistic classification task (PCT). In this paradigm, subjects appear to implicitly learn cue–response associations gradually over many trials (Knowlton, Squire, & Gluck, 1994). It is not known whether learning of these associations is affected by divided attention in the same way that learning can be affected in the SRT by performance of a secondary task. The PCT shares with the SRT the general pattern of intact performance by amnesic patients and impaired performance in patients with basal ganglia damage, suggesting that learning on these tasks relies on the same neural systems for acquisition (Knowlton et al., 1996; Knowlton et al., 1994). In contrast to visuomotor skills, such as rotor pursuit and SRT, there is no external signal guiding performance on the PCT. Rather, the subject has to generate a response, learning to respond accurately over trials on the basis of feedback. In a previous study of dual-task effects on visual category learning, it was found that a secondary task interfered with the learning of an explicit, verbalizable rule that determined category membership, but not with the learning of a task in which category membership was determined by a rule that was not easily verbalized and was learned gradually by the implicit integration of information across trials (Waldron & Ashby, 2001). In that study, the timing of the primary and secondary tasks was prescheduled for subjects. The response to the primary task was completed first, and the response to the secondary task was always made afterward. However, as Hsiao and Reber's (2001) study has shown, the timing of the interfering task appears to be critical in the SRT paradigm and may also be so in cognitive skill learning. As on the SRT task, a response deadline may be imposed on the PCT, and subjects must schedule their response within a specific interval. Interference with a response selection phase by a secondary task might depress performance without affecting learning. It is of interest whether learning may be preserved in a situation in which an attentional manipulation interferes with performance.

Here, we report two experiments in which the effects of a concurrent working memory task on classification learning were addressed. Experiment 1 measured the effect of a secondary task on PCT performance, and Experiment 2 used a design including probe blocks to assess learning in the absence of possible secondary-task effects on performance. We also assessed the effects of the secondary task on the acquisition of explicit knowledge of cue–outcome associations. Previous research has suggested that although explicit knowledge is not necessary for learning on the PCT, some explicit knowledge of the associations can be acquired in parallel (Reber, Knowlton, & Squire, 1996). Reber and colleagues used three tests to assess the flexibility of knowledge acquired about associations between cues and outcomes during performance of the PCT: (1) estimating association strengths between single cues and outcomes, (2) estimating association strengths of cue pairs with outcomes, and (3) selecting single cues, cue pairs, and three-cue combinations most strongly associated with an outcome. In an additional experiment done by Reber et al. (1996), subjects rated how directly these tests assessed their knowledge, varying from a reinstatement of the PCT situation to requiring use of the knowledge in a new and flexible way. It was reported that estimating the association strength of weakly associated cues required more flexible knowledge than did selecting combination cues in the third test. Because a secondary task is expected to impair explicit learning, we predicted that it would result in less flexible explicit knowledge of the cue–response associations learned on the PCT.

GENERAL METHOD

Apparatus

In both Experiments 1 and 2, a PCT was administered to subjects on a Macintosh PowerBook G4. The task was programmed in a MatLab environment using the Psychophysics Toolbox (Brainard, 1997). Responses were made on a custom button box.

Task and Procedure

The PCT version used in these experiments had the same stimuli and cover story as those in previous studies (Aron et al., 2004; Shohamy et al., 2004). The subjects were told to pretend that they worked in an ice cream shop and that they would learn to predict whether each "customer" preferred chocolate or vanilla ice cream. On each trial, a toy figure (Mr. Potato Head, Playskool/Hasbro), on which four different features could be placed (bow tie, mustache, glasses, and hat), was presented. Stimulus presentation lasted 3 sec, during which the subjects responded by pressing the left button to predict chocolate and the right button to predict a vanilla ice cream preference. This deadline procedure has typically been used in the PCT and is thought to encourage subjects to respond on the basis of stimulus–response habits, rather than reflecting on explicit memory for the outcome of previous trials. Feedback was then shown for 1 sec by presenting the figure with a chocolate or vanilla ice cream cone in its hand, followed by a 500-msec interval before the next trial. The Mr. Potato Head figure wore from one to three of the four features on each trial, yielding 14 combinations, and the cue strength of each of the 14 resulting stimuli were such that the overall probability associating each feature with chocolate was .756, .575, .425, and .244 across 100 trials (see Table 1). Although the stimuli differ, this task is structurally isomorphic to the *weather prediction* task used in previous studies of probabilistic classification learning (e.g., Knowlton et al., 1996; Knowlton et al., 1994). A correct answer consisted of predicting the outcome most strongly associated with a figure. Because the association was probabilistic, a subject could make a correct prediction and receive feedback inconsistent with that prediction. As in previous studies, trials occurred in a random but fixed order for all the subjects (e.g., Gluck, Shohamy, & Myers, 2002). The overall probabilities were as described above (and in Table 1) within each 100 trials. Each outcome did not occur on more than 4 consecutive trials.

Dual-task blocks consisted of a secondary tone-counting task in addition to the PCT. Two types of tones, high-pitched tones (1000 Hz) and low-pitched tones (500 Hz), were played during each trial on dual-task blocks. Each 3-sec trial was divided into 12 intervals of 250 msec, and the tones could occur in Intervals 3–10 (500–2,500 msec after trial onset). The number of tones presented on each trial varied randomly between one and three, averaging two

Table 1
Relations Among Stimuli, Features, and Outcomes

Stimulus	Feature: Hat	Glasses	Mustache	Bow Tie	Frequency	*P*(Choc)
1	0	0	1	1	9	.889
2	0	0	0	1	14	.857
3	0	1	0	1	6	.833
4	0	1	1	1	4	.750
5	1	0	1	1	3	.667
6	0	0	1	0	8	.625
7	0	1	1	0	6	.500
8	1	0	0	1	6	.500
9	0	1	0	0	8	.375
10	1	1	0	1	3	.333
11	1	1	1	0	4	.250
12	1	0	1	0	6	.167
13	1	0	0	0	14	.143
14	1	1	0	0	9	.111
Total	.244	.425	.575	.756	100	.500

Note—1 denotes the presence of a cue. The 14 stimuli were composed of one to three of four features: bow tie, mustache, glasses, and hat. Each stimulus occurred with a certain frequency and probability across each set of 100 trials. The bottom row lists the ovarall *P*(Choc) for the four features across all stimuli.

per trial, and occurred randomly within the eight possible intervals. Whether the tone was high or low pitched was also random, with the total number of high tones presented in a block varying between 30% and 70% of the total number of tones presented. The subjects were required to keep a running count of high-pitched tones while ignoring the low-pitched tones throughout an entire block. At the end of the block, they reported the total number they counted. The tone-counting task was used in order to avoid sensory or motor conflict with the PCT. Whereas cues in the PCT were presented visually, the stimuli in the tone-counting task were auditory. Also, the tone-counting task did not require a response during the PCT trials that could interfere with the keypress response. The tone-counting task introduced a concurrent working memory load, which we predicted would disrupt explicit memory encoding.

After training, a subset of the subjects performed tests of cue knowledge similar to those used by Reber et al. (1996). These tasks were designed to assess explicit knowledge of the cue–outcome associations that could be used flexibly, in that the subjects were required to use their knowledge in situations that were different from the training context (cf. N. J. Cohen & Eichenbaum, 1993). In the cue estimation task, the subjects were asked to estimate the percentage of time that the various characters would prefer chocolate or vanilla. They were asked about the four single features and the six combinations of two features. Because two of the two-feature combinations had a .5 probability association with each outcome, the estimates for these two were collapsed in the analyses. Each subject was asked to make estimates for either chocolate or vanilla, and the estimates were averaged across question type to get a number associated with each cue from most to least predictive. The difference between estimates and actual cue value was also calculated for each cue. In the cue selection task, the subjects were asked to pick from a lineup the character that they would most likely see, given a specific ice cream flavor outcome. They were asked to select from figures wearing a single feature, feature pairs, and combinations of three features in turn. For single-feature selection, a score between one and four was given—one point for selecting the most predictive of the four features, two for the second-most predictive and so forth. For selection of feature pairs, points were assigned for each selected feature and summed, resulting in scores between three and seven, which were recalculated to a 1–4 scale as follows: score $*$ $0.75 - 1.25$. Selection of figures wearing three features was scored with one point for selecting the most predictive cue combination and so on down to four points for the least predictive cue combination (chance = 2.5 on the 1–4 scale).

EXPERIMENT 1

In Experiment 1, we investigated the effect of a secondary task on the performance of the PCT task and on measures of explicit cue–outcome association knowledge. Dual-task performance was expected to disrupt explicit knowledge of cue–outcome associations. Performance of a secondary task might interfere with performance on the PCT, as is the case for some SRT sequences. On the other hand, performance might be unaffected by the concurrent task if both learning and performance can proceed in an automatic fashion.

Method

Subjects. Sixty-four right-handed undergraduate students participated in this study (45 of them female). The mean age was 20.1 years ($SD = 3.1$; range, 18–35). All the subjects were recruited from the

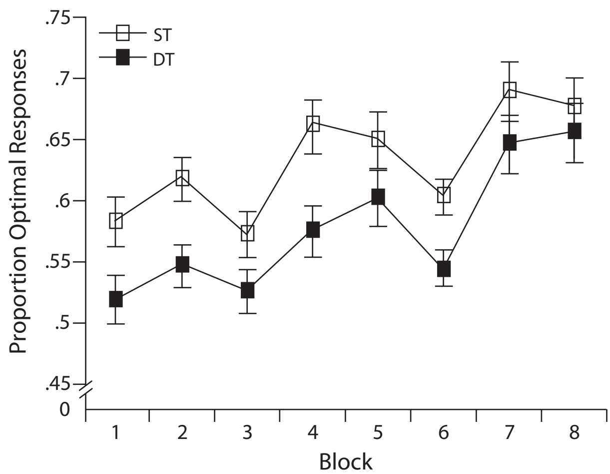

Figure 1. Proportions of optimal responses on the probabilistic classification task in Experiment 1. Error bars represent the standard error of the mean. ST, single-task group; DT, dual-task group.

UCLA undergraduate subject pool, which consists of students in introductory classes receiving credit for participation. The subjects provided informed consent in accordance with the Office for the Protection of Human Research Subjects at UCLA.

Experimental design. A single-task (ST) group performed only the PCT, and a dual-task (DT) group performed the secondary tone-counting task in addition to the PCT. The subjects were randomly assigned to one of two groups and completed a total of 320 trials divided into eight blocks. The subjects were allowed to rest as long as they wanted between each block. Because the probabilities described were derived across each set of 100 trials, the probabilities across the entire 320 trials were slightly different from those across each set of 100 trials. Twelve subjects did not complete the cue knowledge tasks because the program implementing these tasks was not available at the time of testing for these subjects.

Results and Discussion

Data were analyzed using repeated measures ANOVA with Huyhn–Feldt correction for nonsphericity.

Accuracy. A response was scored as correct if the subject selected the outcome that was more strongly associated with the cue combination present on that trial. Cue combinations equally associated with both outcomes were excluded from analysis. Single- and dual-task performance was compared in a 2 (group) × 8 (block) ANOVA. A main effect of group [$F(1,62) = 8.07, p = .006$] indicated that the ST group performed more accurately than the DT group. There was a main effect of block [$F(7,434) = 16.38, p < .001$] and no interaction between group and block ($F < 1$). Both groups improved their performance across training and did so essentially in parallel (Figure 1). These results indicated that the secondary task impaired performance on the PCT. However, concurrent performance of the secondary task did not preclude some degree of performance improvement. The rate of improvement appeared to be similar in the two groups, suggesting that the interference from the secondary task may have caused a general performance decrement (perhaps reflecting a speed–accuracy trade-off, as will be discussed below).

Although there was no interaction between group and block, there was a numerically smaller difference between the groups at the end of training. Pairwise comparisons of groups on each block showed that the difference between the groups on the last two blocks did not achieve statistical significance. It is possible that the DT group began to overcome the effects of the dual task across training. Interestingly, the difference between groups emerged quite quickly and was apparent even on the first 10 trials [$t(62) = 2.54, p = .014$]. Whereas the ST group showed evidence of some learning on the first 10 trials, the DT group performed near chance levels for the first block. When performance on these first 10 trials was broken down trial by trial, it appeared that the ST group was able to take advantage of an early trial repetition that the DT group was not. As is indicated by the lack of an interaction between group and block, the group difference that emerged early generally persisted across training.

Reaction time. RT analyses were restricted to trials on which the subjects responded correctly. In a 2 (group) × 8 (block) ANOVA, there was a main effect of block [$F(7,434) = 13.66, p < .0001$], with RTs decreasing across training. Neither the group difference nor the interaction was significant (Fs < 1; see Figure 2). Although the group difference was not statistically significant, the numerical RT difference between the groups suggests that imposing the secondary task caused the subjects to devote less time to the processes required for performance of the PCT.

Secondary task. Accuracy on the secondary task was measured as the percentage of tone-counting deviations on each block. The absolute difference between the reported number of counted tones and the number of target tones was divided by the target number and multiplied by 100. Accuracy on the secondary task was high. Tone-counting errors were below 11% on all blocks (see Table 2). A repeated measures ANOVA showed no main effect of block [$F(7,217) = 1.06, p = .379$]. Importantly, there was no decrease in accuracy across blocks, suggesting that improved performance on the primary task across training was not due to an accuracy trade-off between the primary and the secondary tasks. There were also no correlations

Table 2
Tone-Counting Errors

Group	Block 1	2	3	4	5	6	7	8
Experiment 1								
Dual task								
M	10.24	8.34	6.39	7.16	5.15	9.21	7.46	7.97
SE	3.26	1.79	1.57	1.24	1.27	2.74	1.42	2.05
Experiment 2								
Dual task mixed								
M	8.86		7.05	5.00	5.51	6.88		5.36
SE	1.62		2.10	1.37	1.39	1.75		1.20
Single task mixed								
M		9.18					4.10	
SE		3.74					1.02	

Note—The values represent the means and standard errors of the percentages of tone-counting deviations. The deviation measure was calculated as the absolute difference between the reported number of tones and the target number of tones divided by the target number and multiplied by 100.

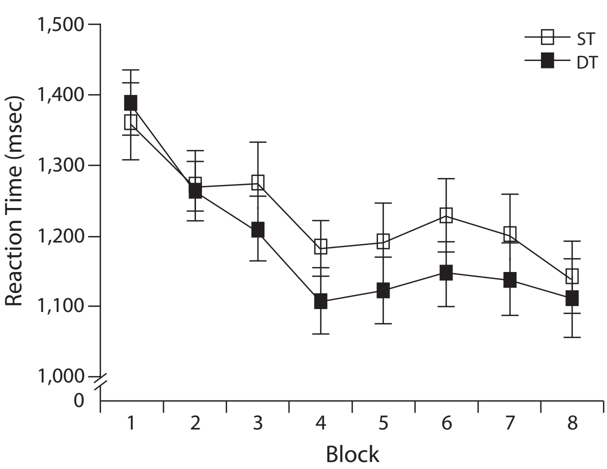

Figure 2. Reaction times on the probabilistic classification task in Experiment 1. Error bars represent the standard error of the mean. ST, single-task group; DT, dual-task group.

Table 3
Cue–Outcome Association Strength Estimates

Group	Cue Pattern 1	2	3	4	1,2	1,3	2,3	3,4	1,4/2,3
				Experiment 1					
Single task									
M	26.23	24.32	20.23	17.43	20.89	31.49	30.43	19.88	13.75
SE	4.70	3.09	3.34	4.54	4.45	5.63	5.26	4.07	2.76
Dual task									
M	32.43	24.33	27.83	27.33	37.03	43.59	33.20	18.32	13.25
SE	4.03	2.65	2.86	3.88	3.81	4.82	4.51	3.49	2.36
				Experiment 2					
Dual task mixed									
M	28.21	27.50	24.73	32.55	25.86	35.43	33.12	29.52	12.60
SE	5.02	3.56	3.27	5.01	4.11	4.98	3.64	4.84	2.25
Single task mixed									
M	30.81	24.82	24.29	27.99	31.00	33.31	26.29	29.81	12.95
SE	4.84	3.43	3.15	4.82	3.96	4.80	3.51	4.66	2.17

Note—The values are the means and standard errors of the absolute difference between subjects' estimates of the percent chance of an outcome associated with the cue pattern presented and the actual percent associated with the pattern.

between tone-counting errors and accuracy on any blocks (*r*s between $-.300$ and .099, all *p*s $> .05$).

Cue knowledge tests. For the judgments on single-cue patterns, a 2 (group) $\times$ 4 (single-cue patterns) ANOVA was performed on the absolute difference between the estimates and the actual probabilities associated with the cues. There was a main effect of group, with the DT group being less accurate in their cue estimates [$F(1,50) = 4.16$, $p = .047$; see Table 3]. The main effect of cue [$F(3,150) = 1.42$, $p = .244$] and the interaction ($F < 1$) were not significant. For the judgment of two-cue patterns, the two combinations with probabilities of .5 were collapsed, resulting in a 2 (group) $\times$ 5 (two-cue patterns) ANOVA that showed the DT group being less accurate on these cues as well [$F(1,50) = 4.89$, $p = .032$]. There was also a significant effect of cue [$F(4,200) = 10.47$, $p < .001$], but the interaction of cue and group was not significant [$F(4,200) = 1.72$, $p = .15$; see Table 3]. These results revealed that the ST group was generally better at estimating the actual value of cues.

Cue selection scores were entered into a 2 (group) $\times$ 3 (number of cues present) ANOVA, and there was a main effect of number of cues present [$F(2,100) = 7.39$, $p = .001$], indicating that the subjects were better at selecting the figure associated with a given outcome when only one cue was present (see Table 4). Although the ST group was numerically closer to a perfect score of 1, the group difference was only marginally significant [$F(1,50) = 2.24$, $p = .141$], and there was no interaction between cue and group ($F < 1$). This task may not have been as sensitive as the cue estimation task, given the limited range of responses the subjects could make.

The secondary task interfered with performance on the PCT but did not appear to result in a complete prevention of learning, given that the DT group did improve across training. The lack of an interaction between group and block is also consistent with the idea that the groups learned at a similar rate but that the DT group suffered from a general performance deficit. In addition, imposing a secondary task impaired the quality of the explicit knowledge acquired by the DT group, leaving them less able to accurately estimate cue–outcome associations.

Under dual-task conditions, the subjects made faster responses on the PCT. Their poorer performance on the PCT could thus be interpreted as a speed–accuracy trade-off. The working memory load imposed by the concurrent task may have caused the subjects to respond more quickly in order to schedule both responding on the PCT and updating the tone count within the response deadline. It is likely that these faster responses were less well prepared than the slower responses in the ST group, with poorer retrieval of the relevant stimulus–response associations.

Because it appears that implicit learning can support performance of the PCT, the subjects in the DT group may have acquired less implicit knowledge of cue–outcome associations, leaving the DT group with less knowledge to support performance. These subjects also appeared to have learned less explicit knowledge about the cue–

Table 4
Cue Selection Task Scores

Group	Cue Pattern Selection Task: One	Two	Three
	Experiment 1		
Single task			
M	1.64	1.82	2.25
SE	0.18	0.16	0.18
Dual task			
M	2.07	2.01	2.38
SE	0.15	0.13	0.16
	Experiment 2		
Dual task mixed			
M	1.79	2.05	2.15
SE	0.15	0.16	0.17
Single task mixed			
M	1.95	1.94	2.29
SE	0.15	0.15	0.17

Note—The values are cue selection scores. The highest possible score is 1, and the lowest is 4. A score of 2.5 is chance performance.

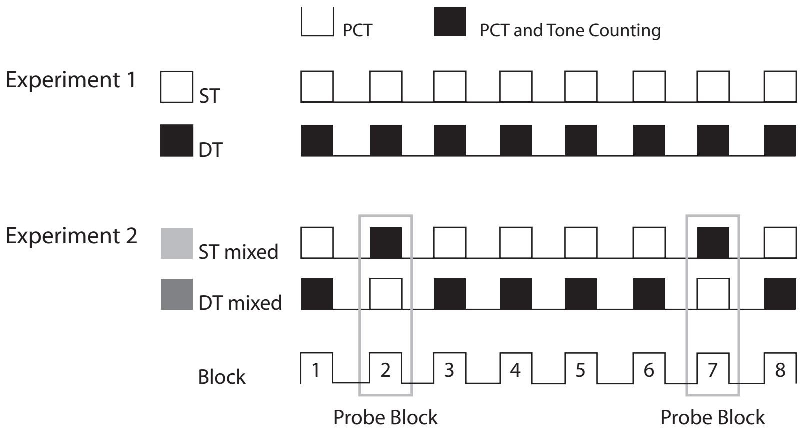

Figure 3. Schematic of the tasks performed on each block by each group in Experiments 1 and 2, indicating which blocks are "probe blocks" in Experiment 2. ST, single task; DT, dual task.

outcome associations, and it is possible that this led to the group difference in performance. However, it is also possible that the subjects in the DT group had normal implicit learning of cue–outcome associations but were unable to fully express this learning due to response selection costs associated with performing the concurrent task. In order to distinguish between these alternatives, we carried out a second experiment in which single-task probe blocks were inserted during dual-task training. In this way, we were able to assess learning in this group independently of the effects of the secondary task on performance.

EXPERIMENT 2

The results of Experiment 1 indicated that attention was required for intact performance of the PCT. However, this experiment was unable to distinguish between whether attention was necessary for learning, performance, or both. Experiment 2 was designed to dissociate concurrent task effects on learning versus performance of the PCT. Two groups performed the PCT. A single-task group (ST-mixed) learned mainly under single-task conditions but performed a secondary tone-counting task during one block early in training and one block late in training (see Figure 3). This group should learn as well as the ST group in Experiment 1, but performance should be impaired on blocks in which they performed the secondary task. If performance of the secondary task impairs PCT performance and not learning, this group should experience performance decrements equivalent to those for the group receiving primarily dual-task training. The second group (DT-mixed) performed mainly under dual-task conditions but performed the PCT without the secondary task during one block early and one block late in training. If the dual task interferes with performance, rather than with learning, the removal of the secondary task should allow the DT-mixed group to perform as well as an ST-mixed group on these blocks. However, given that the DT-mixed group learned mainly under dual-task conditions, performance on tests of explicit cue knowledge may still be impaired, in comparison with groups learning under single-task conditions. Thus, performance of the secondary task may have differential effects on the learning of explicit and implicit knowledge of cue–outcome associations.

Method

Subjects. Sixty-eight right-handed undergraduate students participated in this study (48 of them female). The mean age was 20.1 years (*SD* = 3.2; range, 18–37). Only right-handed subjects were recruited. All the subjects were recruited from the UCLA undergraduate subject pool and received credit for participation. The subjects provided informed consent in accordance with the Office for the Protection of Human Research Subjects at UCLA. Eleven subjects did not complete the cue knowledge tasks because the program implementing these tasks was not available at the time of testing for these subjects.

Experimental design. The subjects were randomly assigned to one of two groups and completed a total of 320 trials, divided into eight blocks. Both groups performed the PCT on all blocks and were required to perform the secondary tone-counting task on some blocks. The ST-mixed group performed the PCT mainly under single-task

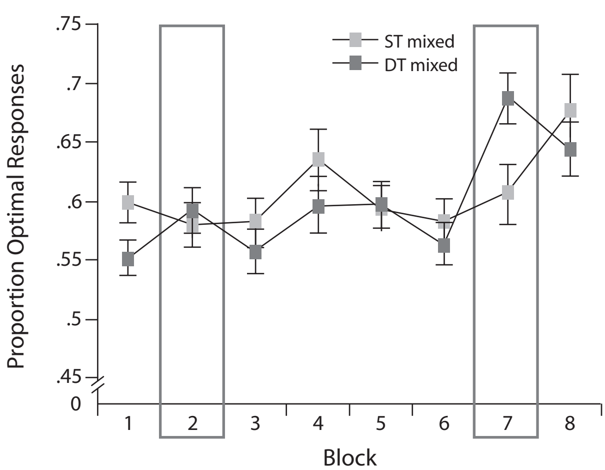

Figure 4. Proportions of optimal responses on the probabilistic classification task (PCT) in Experiment 2. Boxes indicate probe blocks. Error bars represent the standard error of the mean. ST, single task; DT, dual task.

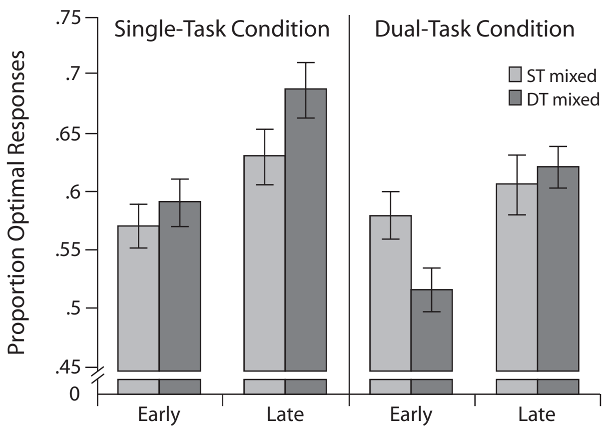

Figure 5. Proportions of optimal responses on the probabilistic classification task in Experiment 2 showing performance in early and late blocks under single-task (ST) and dual-task (DT) conditions. Error bars represent the standard error of the mean.

conditions, and the DT-mixed group performed mainly under dual-task conditions. Probe blocks were inserted early and late in training, during Blocks 2 and 7. During these probe blocks, the ST-mixed group performed the tone-counting task in addition to the PCT, and the DT-mixed group performed only the PCT (see Figure 3).

Results and Discussion

Three subjects' data were excluded from further analysis due to computer malfunction or responding on fewer than 50% of the trials in a trial block.

Accuracy. Accuracy was compared separately for probe and nonprobe blocks. For the analysis of the nonprobe blocks, the groups were compared in a 2 (ST-mixed/DT-mixed group) $\times$ 6 (block) ANOVA. The pattern of results was similar to that in Experiment 1. There was a main effect of block [$F(5,315) = 9.23$, $p < .0001$] due to increasing accuracy across training. The ST-mixed group performed better than the DT-mixed group numerically, but this difference was not significant [$F(1,62) = 1.64$, $p = .205$]. The group $\times$ block interaction was not significant either ($F < 1$; see Figure 4).

In order to compare the two groups under single- and dual-task conditions, we compared probe performance of each group with performance of the other group on trials occurring near the same point in training as the probe blocks. For the ST-mixed group, we collapsed the 20 trials before and after each probe block to compare with probe performance of the DT-mixed group in order to compare both groups under single-task conditions. To compare the groups under dual-task conditions, we compared the probe performance of the ST-mixed group with the performance on the 20 trials before and after the probe blocks for the DT-mixed group. In this way, we were able to compare the groups under both single- and dual-task conditions early and late in training at the same average number of training trials.

To specifically explore whether the groups performed similarly when tested under single-task conditions, we performed a 2 (ST-mixed/DT-mixed group) $\times$ 2 (block) ANOVA only on single-task blocks. This analysis showed a main effect of block [$F(1,63) = 24.23$, $p < .0001$], no significant effect of group [$F(1,63) = 2.29$, $p = .135$], and no interaction with group [$F(1,63) = 1.35$, $p = .249$], indicating that training under dual-task conditions allowed the DT-mixed group to learn as much under dual-task conditions as the group learning under single-task conditions (see Figure 5).

We also compared the performance of the ST-mixed and the DT-mixed groups on dual-task blocks. A 2 (ST-mixed/DT-mixed group) $\times$ 2 (block) ANOVA performed only on dual-task blocks showed a main effect of block [$F(1,63) = 15.49$, $p < .001$], a group $\times$ block interaction [$F(1,63) = 5.62$, $p = .02$], and no main effect of group [$F(1,63) = 1.04$, $p = .312$]. The ST-mixed group performed better than the DT-mixed group under dual-task conditions early in training, whereas the DT-mixed group performed slightly better under dual-task conditions at the end of training. Performance of the DT-mixed group under dual-task conditions improved greatly, whereas the ST-mixed group performance did not change much from early to late dual-task blocks. The better performance of the ST-mixed group on the initial dual-task probe block may indicate that early in training, learning under single-task conditions resulted in knowledge that was relatively robust under dual-task conditions. However, the lack of a difference between the groups when tested under single-task conditions indicated that the overall levels of learning in the two groups were similar.

The fact that the two groups performed similarly when conditions were the same suggests that the dual-task condition did not impair learning. However, it is possible that the groups did not differ because learning in the ST-mixed group was impaired, due to the inclusion of dual-task probe blocks. In order to provide a stronger test of whether learning was normal in the DT-mixed group, we compared their performance on the probe single-task blocks with the performance of the ST group in Experiment 1 on comparable blocks (Blocks 2 and 7). A 2 (ST/DT-mixed group) $\times$ 2 (block) ANOVA on performance on the probe blocks showed that there was no significant group difference when the DT-mixed group was allowed to perform under single-task conditions ($F < 1$). On the early blocks, means were .618 ($SE = .020$) and .591 ($SE = .019$) for the ST (Experiment 1) and DT-mixed (Experiment 2) groups, respectively. On late blocks, means were .691 ($SE = .023$) and .687 ($SE = .022$). In this analysis, there was a significant block effect [$F(1,66) = 22.20$, $p < .0001$] but no significant interaction ($F < 1$), indicating that both groups improved their performance across the early to late blocks.

We also undertook a similar cross-experiment analysis to compare dual-task performance of the ST-mixed group with that of the DT group. A 2 (DT/ST-mixed group) $\times$ 2 (block) ANOVA on probe blocks showed an effect of block [$F(1,59) = 11.07$, $p = .002$] but no effect of group ($F < 1$). The group $\times$ block interaction was nearly significant [$F(1,59) = 3.82$, $p = .055$], due to the DT group's showing greater improvement across training. This suggests, as was mentioned above, that the DT group in Ex-

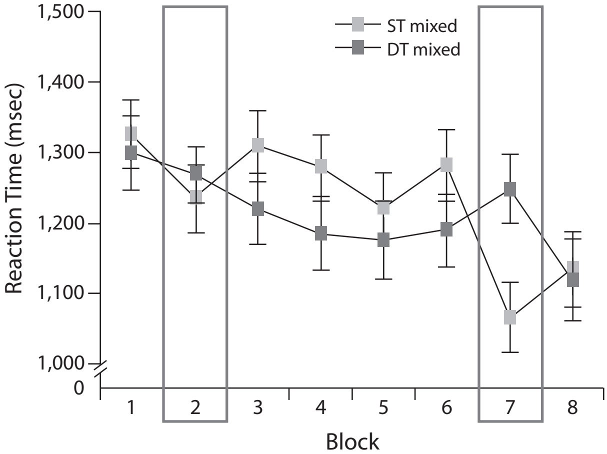

Figure 6. Reaction times on the probabilistic classification task in Experiment 2. Boxes indicate probe blocks. Error bars represent the standard error of the mean. ST, single task; DT, dual task.

periment 1 may eventually have overcome the interference from the secondary task.

Reaction time. RTs for correct trials of the ST-mixed and DT-mixed groups were entered into a 2 (ST-mixed/DT-mixed group) × 6 (block) repeated measures ANOVA. There was a main effect of block [$F(5,315) = 9.16$, $p < .0001$], with RTs decreasing across training (see Figure 6). There was no significant effect of group or interaction between group and block (Fs < 1).

Trials surrounding the probe blocks were collapsed, as was done for accuracy, and entered into a 2 (ST-mixed/DT-mixed group) × 2 (block) × 2 (single-task/dual-task condition) ANOVA. There was a main effect of block [$F(1,63) = 26.60$, $p < .0001$], indicating a general decrease of RTs with training. A main effect of condition was seen [$F(1,63) = 17.55$, $p < .0001$], due to shorter RTs under dual-task conditions. A condition × group interaction [$F(1,63) = 5.42$, $p = .023$] indicated that the speed-up generally seen under dual-task conditions was more pronounced in the ST-mixed group, which was less accustomed to performing under dual-task conditions (see Figure 7). There were marginally significant block × task [$F(1,63) = 3.82$, $p = .055$] and block × group [$F(1,63) = 3.44$, $p = .068$] interactions. No other effects were significant (ps $> .1$).

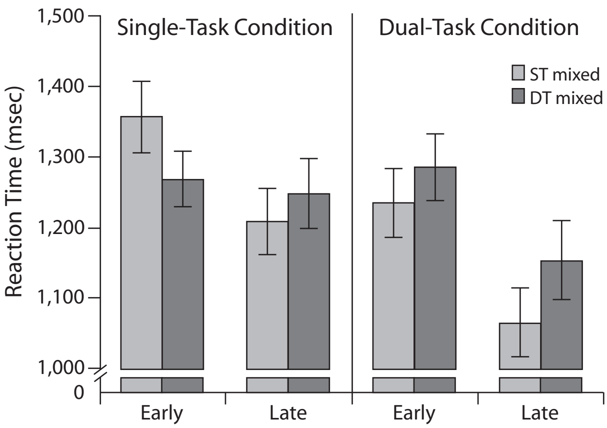

Figure 7. Reaction times on the possibilistic classification task in Experiment 2, showing performance in early and late blocks under single-task (ST) and dual-task (DT) conditions. Error bars represent the standard error of the mean.

Secondary task. Accuracy on the secondary task was measured as the percentage of deviation of tone counting on each block. In the DT-mixed group, there were six blocks with the secondary task, and in the ST-mixed group, there were two blocks with the secondary task. Percentage of deviation from the actual tone count was below 10% on all the blocks. There was no decrease in secondary-task accuracy in either group, indicating that a performance trade-off did not account for the increased accuracy on the primary task (see Table 2).

Cue knowledge tests. Given that the DT-mixed group was able to perform as well as the ST group when allowed to perform under single-task conditions, it appears that implicit learning of the cue–outcome associations was intact in this group. However, it is possible that learning under dual-task conditions impaired explicit learning of cue–outcome associations. We performed two sets of analyses. First, we compared the performance of the DT-mixed group with that of the ST group in Experiment 1. Since the comparison of PCT performance during probe blocks provided the strongest evidence that dual-task training did not impair PCT learning, it was important to compare these two groups on explicit knowledge of cue–outcome associations. In addition, we also compared the DT-mixed and the ST-mixed groups in Experiment 2 on the explicit knowledge measures.

We first compared the DT-mixed group with the ST group on the absolute difference between the estimated and the actual probabilities associated with cues (see Table 3). A 2 (DT-mixed/ST group) × 4 (single-cue stimuli) ANOVA showed that the DT-mixed group was less accurate in their cue estimates [$F(1,46) = 5.14$, $p = .028$]. No other effects were significant ($F < 1$). For the stimuli showing two cues, the DT-mixed group was numerically less accurate as well, but a 2 (group) × 5 (two-cue stimuli) ANOVA did not reach significance [$F(1,46) = 2.037$, $p = .160$]. There was an effect of cue type [$F(4,184) = 7.28$, $p < .0001$]. Estimates were less accurate on the more ambiguous cues that were combinations of cues associated with opposite outcomes. There was no significant interaction of group and cue type ($F < 1$).

For the cue selection task, scores were entered into a 2 (DT-mixed/ST group) × 3 (number of cues present) ANOVA, which showed a main effect of number of cues present, with better performance when the subjects chose among figures with only one cue present [$F(2,92) = 9.37$, $p < .001$]. There was no significant group difference ($F < 1$) and no interaction [$F(2,92) = 1.16$, $p = .319$], although the ST group performed numerically better (see Table 4).

Unlike the comparison of the ST and the DT-mixed groups described above, explicit knowledge of the cue–

outcome associations was similar for the ST-mixed and the DT-mixed groups in Experiment 2. Both groups performed similarly to the DT group in Experiment 1. A 2 (ST-mixed/DT-mixed group) $\times$ 4 (single-cue stimuli) ANOVA performed on the difference between the actual and the estimated cue strengths did not show any significant effects (Fs < 1). For the two cue stimuli, there also was no effect of group ($F < 1$), but the 2 (group) $\times$ 5 (two-cue stimuli) ANOVA did show a main effect of cue [$F(4,208) = 8.15$, $p < .001$], with the poorest accuracy being on estimates of the cues combined from individual cues associated with opposite outcomes. The interaction was not significant ($F < 1$). In the analysis of scores on the cue selection task a 2 (ST-mixed/DT-mixed group) $\times$ 3 (number of cues present) ANOVA showed a main effect of cue [$F(2,104) = 3.95$, $p = .022$], with performance deteriorating when more cues had to be selected. There was no significant group difference or interaction (Fs < 1). In general, both groups performed more poorly than the ST group, as was indicated by the significant differences between the ST group and the DT-mixed group discussed above. It might be the case that inclusion of dual-task blocks in the ST-mixed group resulted in less acquisition of explicit knowledge of cue–outcome associations than in the ST conditions.

Although the DT-mixed group exhibited significantly less explicit knowledge of the cue–outcome associations than did the ST group, there still was variability in this group in terms of how much knowledge was gained. In the DT-mixed group, 13 subjects performed at or below chance levels[1] on the cue estimation task and were classified as unaware, whereas for 13 subjects, estimates were at least numerically in the correct direction and were classified as more aware. For the ST group, only 3 of the 22 subjects could be classified as unaware by this criterion. In order to assess the effect of awareness on PCT performance, we compared the performance of unaware and more aware DT-mixed subjects on the two probe blocks. We restricted our analysis to the DT-mixed group because there were adequate numbers of unaware subjects and we had a measure of the performance of this group under single-task conditions in the probe blocks, using a 2 (awareness subgroup) $\times$ 2 (block) ANOVA on accuracy scores. We found that there was a main effect of group [$F(1,24) = 6.33$, $p = .019$], with the more aware subjects performing better than the unaware subjects. There was also a block effect [$F(1,24) = 13.89$, $p = .001$], with no group $\times$ block interaction [$F(1,24) = 1.39$, $p = .264$], showing that both groups improved performance across training. One possible reason for the group difference is that there may have been factors that differed between the two groups, such as motivation level, that led to better PCT performance and more accurate cue estimates. Another possibility is that having at least some awareness of the cue–outcome associations can augment PCT performance. However, the relationship between explicit knowledge and PCT performance is not particularly close, in that PCT performance on probe blocks was not better in the ST group than in the DT-mixed group, despite the significant difference in the amount of explicit knowledge for these two groups. It is also important to note that even the unaware DT-mixed group showed significant learning of the PCT, with performance on the second probe block significantly above chance [$t(12) = 4.28$, $p = .001$], and there was a strong trend for improvement across probe blocks [$F(1,12) = 4.47$, $p = .056$]. These results are consistent with the idea that explicit knowledge of cue–outcome associations is not necessary for learning on the PCT.

GENERAL DISCUSSION

The present results show that a secondary task disrupts performance of the PCT but that acquisition of the cognitive skill can proceed similarly under single- and dual-task conditions. Although the proportion correct scores were lower in both experiments when the subjects were concurrently performing a task that taxed working memory, performance on single-task probe blocks indicated that these subjects had acquired implicit knowledge of the cue–response associations normally. However, despite apparently normal learning of implicit cue–outcome associations in the PCT, the subjects in the dual-task condition showed poorer flexible knowledge of the cue–outcome relationships.

The performance of a concurrent task has been shown to disrupt performance in a wide variety of task situations (see Pashler, 1994, for a review). According to one view, performing a concurrent task depletes mental resources that are needed to accomplish the primary task (Kahneman, 1973). Consequently, one might expect a disruption of cue–response association learning if a general mental resource is depleted by performance of the tone-counting task. However, according to another view, the concurrent memory load has a more specific effect on response preparation (Logan, 1978). Thus, rehearsing and updating the tone count may interfere with the retrieval of stimulus–response associations or the use of these associations in preparing a response.

The demonstration of a performance decrement in the absence of a learning deficit is consistent with Logan's (1978) proposal and may be the result of a need for response scheduling in the experiments presented here. In the present study, the subjects had to both make a response to the PCT and update their count of tones on each trial within a set time window. In this regard, the structure of the task is similar to most SRT tasks. The PCT is not essentially a speeded task, in the sense that increasing speed is not a goal of training, but the patterns of RTs in the various groups could indicate a scheduling conflict. Performance appeared to settle into a pattern that was perturbed when task requirements changed. In Experiment 2, the ST-mixed group's RTs shortened when they were required to perform the secondary task late in training, and performance suffered. The DT-mixed group showed lengthened RTs when it was not required to perform the secondary task late in training, and performance improved. In a study of category learning, Waldron and Ashby (2001) did not find that a concurrent task affected performance of an implicitly learned categorization task. In their experiment, the responses to the primary and secondary tasks were scheduled for subjects in such a way that first a response to the primary task was made and then the response to the secondary task followed, and no response deadline was set. It is possible that the preset timing in that study circumvented a response selection conflict that would lead to a performance deficit. Nevertheless, the lack of an effect of a concurrently performed task on implicit category learning as seen by Waldron and Ashby is consistent with the present findings with the PCT.

Although concurrent performance of the tone-counting task did not disrupt learning of stimulus–response associations, it did impair acquisition of explicit knowledge of these associations. This result is consistent with previous work showing that a concurrent task impairs explicit memory encoding (Craik et al., 1996). The results also parallel those of Jimenez and Vazquez (2005), who found that a secondary tone-counting task interfered less with probabilistic sequence learning than with deterministic sequence learning, which is more likely to be accompanied by explicit knowledge. Explicit and implicit learning of cue–outcome associations in the PCT has been dissociated in the performance of neuropsychological patients (Knowlton et al., 1996), and the present results suggest that performance of a concurrent task can also dissociate these two types of learning within the same task. A hallmark of implicit stimulus–response habit learning may be that it proceeds automatically and independently of attention (Packard & Knowlton, 2002). The present results provide the first direct evidence that human habit learning is not necessarily reliant on available attentional resources.

The finding that a cognitive skill can be acquired during concurrent secondary-task performance is in agreement with findings using visuomotor skill tasks in which a secondary task impaired performance and not acquisition (Eysenck & Thompson, 1966; Frensch et al., 1998). These tasks can be learned implicitly and appear to depend on the striatum for acquisition. The PCT seems to further share some characteristics of the SRT in the possibility of acquiring implicit and explicit knowledge about the task in parallel. Reber and Squire (1998) found that explicit and implicit knowledge in an SRT task was acquired in parallel and was encapsulated, in the sense that knowledge in one domain was unrelated to knowledge in another. Similarly, Waldron and Ashby (2001) found no correlation between learning of implicit and explicit rules.

In the present study, flexible knowledge of cue–outcome relationships did not appear to be necessary for normal acquisition in the PCT, but such knowledge may support performance at some point. Studies of patients with Parkinson's disease have led to the suggestion that after extended training, explicit knowledge may support performance, accounting for the fact that patients eventually show learning on PCTs despite neostriatal dysfunction (Knowlton et al., 1996; Moody, Bookheimer, Vanek, & Knowlton, 2004). Other evidence suggests that performance of patients with Parkinson's disease relies on simple, single-cue associations, which are likely to be learned explicitly (Shohamy, Myers, Onlaor, & Gluck, 2004). The neuropsychological populations usually tested with the PCT have the capacity to acquire either implicit or explicit knowledge to support performance, depending on the brain systems that are intact, whereas the healthy young adults studied here may have acquired both in parallel.

Functional neuroimaging (fMRI) has been used to investigate potential loci of interference in dual-task paradigms. It has been suggested that there may be specific dual-task areas dedicated to resolving interference between tasks without being necessary for performing either task or that, instead, interference between tasks is the result of a brain region's being necessary for performance of both tasks, thus leading to competition for neural resources (e.g., Klingberg, 2000). In the present study, we sought to avoid such overlap with the choice of the secondary task. However, the engagement of working memory seemed to interfere specifically with the preparation/selection of responses. Hazeltine, Bunge, Scanlon, and Gabrieli (2003) found that in addition to material-specific response selection processes, some brain regions appear to be associated with resolution of response competition in general. Occupation of working memory may also have interfered with engagement of processes that support the encoding necessary for explicit memory (see Uncapher & Rugg, 2005). Willingham, Salidis, and Gabrieli (2002) found that engaging explicit memory processes on an SRT task did not preclude acquisition of implicit sequence learning. Instead, implicit learning may have occurred automatically regardless of whether explicit learning occurred in parallel. Consistent with these results, Poldrack et al. (2005) found that activity in the putamen, which showed changes in activity related to sequence learning, was not affected by the presence of a secondary task. A similar process may have occurred on the PCT task in the experiments presented here. However, it does not appear that the superior explicit knowledge of the task structure in the ST group was the most important factor accounting for better performance. Instead, it was the opportunity to perform under single-task conditions.

Although the greater explicit knowledge of the ST group did not translate into better PCT performance, there was evidence that the subjects with at least some awareness of the cue–outcome associations performed better than those with no apparent awareness. It appears that performance of the PCT can be supported by either explicit or implicit knowledge. This may be a general property of many category-learning tasks; good performance may be achieved through multiple learning mechanisms that are likely to depend on different (possibly interactive; Poldrack & Packard, 2003) brain systems.

The present findings underscore the importance of considering the effects of experimental manipulations separately for learning and performance. The results suggest that response selection may be particularly sensitive to the addition of a concurrent task when subjects must schedule responses within a deadline. Although accuracy may decrease due to impaired response selection abilities, the addition of a concurrent working memory load does not appear to impair implicit learning of cue–outcome associations.

AUTHOR NOTE

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NOTE

1. Chance level was defined as the average absolute difference score across all cue estimates that a subject would obtain if he or she estimated a 50% chance of either outcome to all the cue estimates.

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