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Using Dual-Task Methodology to Dissociate Automatic From Nonautomatic Processes Involved in Artificial Grammar Learning

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Previous studies have suggested that both automatic and intentional processes contribute to the learning of grammar and fragment knowledge in artificial grammar learning (AGL) tasks. To explore the relative contribution of automatic and intentional processes to knowledge gained in AGL, we utilized dual-task methodology to dissociate automatic and intentional grammar- and fragment-based knowledge in AGL at both acquisition and at test. Both experiments used a balanced chunk strength grammar to assure an equal proportion of fragment cues (i.e., chunks) in grammatical and nongrammatical test items. In Experiment 1, participants engaged in a working memory dual-task either during acquisition, test, or both acquisition and test. The results showed that participants performing the dual-task during acquisition learned the artificial grammar as well as the single-task group, presumably by relying on automatic learning mechanisms. A working memory dual-task at test resulted in attenuated grammar performance, suggesting a role for intentional processes for the expression of grammatical learning at test. Experiment 2 explored the importance of perceptual cues by changing letters between the acquisition and test phase; unlike Experiment 1, there was no significant learning of grammatical information for participants under dual-task conditions in Experiment 2, suggesting that intentional processing is necessary for successful acquisition and expression of grammar-based knowledge under transfer conditions. In sum, it appears that some aspects of learning in AGL are indeed relatively automatic, although the expression of grammatical information and the learning of grammatical patterns when perceptual similarity is eliminated both appear to require explicit resources.

Keywords: artificial grammar learning, implicit learning, working memory, dual-task, automatic processes

There is general agreement that there may exist two distinct forms of learning, explicit and implicit. Explicit learning refers to learning that happens actively, consciously, and with effort, such as the type of learning that occurs during much of formal education. Implicit learning, on the other hand, occurs more passively, incidentally, and without as much directed effort. Implicit learning is theorized to be involved in procedural motor activities such as riding a bike or typing, as well as in more complex cognitive phenomena such as social interaction and language learning (Reber, 1993).

Artificial grammar learning (AGL) has been a useful paradigm for the study of implicit learning. In the typical AGL paradigm, individuals are shown (or asked to memorize) letter strings that, unknown to them, conform to an artificial grammar. Following presentation of the acquisition exemplars, participants are able to reliably determine whether a newly presented letter string is grammatical according to the artificial grammar, without being able to explicitly verbalize the grammar itself. Reber (1989) interpreted this evidence to suggest that AGL is mediated by implicit learning mechanisms. In other words, he took lack of conscious awareness as proof for the automatic nature of learning mechanisms involved in AGL.

Historically, many researchers have accepted the notion that a lack of consciousness is a strong indication of automaticity, most likely because many assume that conscious awareness is required for intentional processing (Moors & De Houwer, 2006). That is, implicit learning has traditionally been considered both unconscious and automatic, in that the processes underlying implicit learning are thought to happen effortlessly in response to exposure to stimuli, whereas explicit learning requires the active (and conscious) engagement of stimuli via attention and working memory. However, a number of contemporary researchers reject the notion that consciousness and automaticity are mutually exclusive (see Moors & De Houwer, 2006, for further discussion).

In the current article, we wish to avoid the question of whether learning in AGL is conscious or unconscious but, rather, focus on the automaticity itself (or lack thereof) of the learning processes involved. We take a capacity view of automaticity, which describes processes as automatic if they occur with little effort and few resources from limited-capacity attentional mechanisms (Hasher & Zacks, 1979; Kahneman, 1973). In this way, one way to help tease apart whether AGL is mediated by automatic or intentional processing is to use a dual-task designed to disrupt intentional processing. Our reasoning is as follows: If a learning process

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involved in AGL is truly automatic and effortless, then doing a dual-task that taps working memory capacity should have a minimal impact on the outcome of that learning process. In contrast, reducing the availability of intentional resources via a demanding dual-task is expected to have a detrimental impact on performance arising from an intentional learning process. Few AGL studies have taken this approach. Before presenting the current study in detail, we first provide a brief summary of previous research examining sources of knowledge in AGL tasks and the extent to which they are thought to arise from automatic or intentional learning processes.

Multiple Pathways to Learning in AGL?

The extant research literature has identified multiple pathways to learning in the AGL task, some automatic and others more intentional. It was originally theorized that individuals rely on an abstract grammar-learning system, with participants' failures to verbalize the "rules" of the grammar as evidence that the grammar was learned automatically and unconsciously (Reber, 1989). Additional support for an implicit grammar-learning mechanism was provided by what are now referred to as "transfer" experiments. In an AGL transfer experiment, the surface features (e.g., letters) of the acquisition exemplars are changed during the test phase, although the underlying grammar stays the same. Clearly, this would make grammaticality decisions that are based solely on item similarity difficult, if not impossible. Thus, the transfer manipulation is meant to increase reliance on (supposedly implicit) grammatical knowledge divorced from the surface details of the exemplars. Impressively, results from multiple studies have indicated that individuals still successfully demonstrate above-chance classification performance, though the learning is often attenuated (Knowlton & Squire, 1996; Reber, 1989; Tunney & Altmann, 2001; but also see Redington & Chater, 1996, for a more skeptical view).

Skeptics of Reber's (1989) implicit and abstract grammar-learning account, however, have demonstrated that the AGL stimuli provide more than just grammaticality information to learners. Test phase classification judgments are not uniquely dependent upon grammaticality but are also sensitive to the similarity between test items and acquisition exemplars. For instance, in their abstract analogy approach, Vokey and Brooks (1992) suggested that underlying similarity between specific acquisition and test exemplars (i.e., specific similarity) accounts for grammaticality performance, rather than unconscious abstraction of the grammatical patterns. Similarly, Knowlton and Squire (1996) have demonstrated that repetitions in the underlying grammatical structure lead to shared bigrams and trigrams (called "chunks") among the acquisition and test items, resulting in cues that learners can use to determine the grammaticality of test items. When they orthogonally balanced test items so that chunk strength (i.e., the extent to which acquisition and test items share chunks) was equal among grammatical and nongrammatical items, they found independent contributions of both grammaticality and chunk strength to endorsement rates (Chang & Knowlton, 2004; Knowlton & Squire, 1996).

Are these postulated grammar and chunk-learning processes mediated by automatic or intentional learning processes? It appears that at least some chunk knowledge is acquired automatically through low-level perceptual features. Chang and Knowlton (2004) assessed the importance of low-level perceptual features in AGL performance using a balanced chunk strength grammar. They conducted two experiments: one in which they used a concurrent articulatory suppression task during learning (designed to disrupt perceptual processing) and one where they changed the font and case of letters from acquisition to test. In both cases, participants exposed to the manipulation experienced a disruption in chunk sensitivity, suggesting that fragment knowledge may be gained automatically through a perceptual fluency mechanism (Chang & Knowlton, 2004). Research has also shown that individuals do retain some explicit memory of the acquisition item chunks (Dienes, Broadbent, & Berry, 1991) and that participants studying only acquisition bigrams can classify the grammaticality of test items correctly at rates similar to those who received whole exemplar at acquisition (Perruchet & Pacteau, 1990), suggesting that some intentional learning processes could also be at play. Thus, these studies may suggest that individuals may rely on a combination of both automatic and nonautomatic processes to learn chunk information (Knowlton & Squire, 1996; Vokey & Brooks, 1992).

Likewise, it has also been shown that participants do have some conscious awareness of what constitutes grammaticality. For instance, in a study, Dulany, Garlson, and Dewey (1984) were able to indicate which parts of letter strings were grammatical by crossing out ungrammatical portions. Dulany et al. (1984) even suggested that knowledge of chunks forms the basis of grammar-based knowledge through the development of an intentional learning process involving microrules (Pothos, 2007). They suggested that learners develop personal sets of rules based upon chunks commonly seen in the acquisition items. For instance, a learner may notice that V commonly follows X in the acquisition strings, and thus use this rule to decide if items are grammatical during test. Thus, instead of automatic learning of abstract grammatical rules, intentional hypothesis-testing mechanisms might play a larger role. This conclusion is supported by Pothos and Wood (2009), who administered an AGL task to a sample of patients with prefrontal brain injuries. Using the COVIS (Competition between Verbal and Implicit Systems; Ashby & Maddox, 2005) model of category learning as a conceptual framework, Pothos and Wood (2009) argued that when the effects of item similarity (e.g., chunks) are balanced across grammatical (G) and nongrammatical (NG) test stimuli, grammaticality should be based primarily on a verbal hypothesis-testing system. The results indicated that grammar knowledge, but not chunk strength knowledge, was impaired in brain-injured patients, suggesting that rule-based grammar information is acquired exclusively through intentional processing mechanisms, which rely heavily on the prefrontal lobes. As Potho and Wood (2009) pointed out, however, the COVIS model generally involves feedback-based learning, and so in the typical COVIS paradigm hypothesis testing would occur during the training phase. Given the discrete acquisition and test phases of AGL, it is difficult to determine whether hypothesis testing is specific to one phase or occurs in both the training and test phases. The traumatic brain injury (TBI) patients in the Pothos and Wood (2009) study presumably lacked access to verbal hypothesis-testing mechanisms in both the acquisition and test phases, so their data do not provide answers regarding the relative importance of intentional processing mechanisms to each phase.

In summary, although debates remain, the evidence to date suggests some support for the possibility that all four logically possible pathways to knowledge may be available to learners: both fragment and grammar-based information can be learned using either automatic or intentional processes. However, none of the previous studies have systematically investigated the contribution of automatic and intentional learning processes in a single design that controls for the availability of cognitive resources, the availability of grammaticality and chunk information, and the presence or absence of perceptual similarity. Further, few studies have examined the differential role of automatic and intentional learning processes in the acquisition and test phases.

Goals of the Present Study

The goal of the current study is to assess the role of intentional processing mechanisms in AGL, controlling for chunk strength and grammatical knowledge, and using both standard and transfer AGL tasks. In both experiments described here, we attempted to dissociate automatic from nonautomatic forms of learning in AGL by using a dual-task designed to disrupt intentional processing during both acquisition and expression of AGL knowledge.

Very few studies to date have assessed the impact of a dual-task on AGL. Dienes et al. (1991) tested the impact of a concurrent random number generation (RNG) task during acquisition but did not use stimuli balanced for chunk strength. They found that the RNG task interfered with classification performance under both intentional and incidental instruction conditions. Dienes et al. (1991) also implemented different priority conditions for dual-task participants: Some participants were told to emphasize the AGL task, and others were told to give priority to the RNG task. Interestingly, the results indicated that while the RNG task was sensitive to the priority manipulation, AGL performance was not. Dienes et al. (1991) theorized that the presence of impaired classification performance under dual-task conditions in the absence of a priority effect may suggest that there is a resource required for grammar learning that is applied to RNG in an all or none way (such as the articulatory loop). Using the same balanced chunk strength stimuli used in the current study, Chang and Knowlton (2004) tested the role of the articulatory loop in AGL by asking some participants to perform an articulatory suppression task concurrent with training. Results suggested that the articulatory suppression task impaired chunk sensitivity without impacting grammar knowledge, suggesting that chunk sensitivity relies more heavily on phonological processing than grammar learning. Notably, the articulatory suppression task used by Chang and Knowlton (2004) did not involve executive (i.e., intentional) processing, whereas the RNG task used by Dienes et al. (1991) did. That the RNG task, but not articulatory suppression, impaired grammar performance may suggest a role for intentional processing in grammar acquisition. However, Dienes et al. (1991) did not separate the relative contribution of chunk and grammar information, so it is possible that the performance decrements observed may have resulted from impaired chunk sensitivity. One of the goals of the present study is to determine the differential impact of intentional processes on grammar-based and fragment knowledge in AGL.

Given that implicit learning is theorized to happen automatically and without effort, executive functions such as working memory (an intentional process, by definition) should have a minimal impact on automatic processes involved in artificial grammar learning. Thus, task manipulations that restrict learner's ability to use intentional processes should have little impact on automatic sources of knowledge. In contrast, we would expect that the same reduction in intentional processes would have a detrimental impact on sources of knowledge that require intentional processing. Using a standard AGL task, in Experiment 1 we incorporated a dual-task designed to remove the availability of intentional sources of learning during acquisition and/or test, making effortful processing very difficult. Because we incorporate a balanced chunk strength design, the dual-task allows us to determine how much of grammar-based learning and chunk-based learning are dependent on automatic processes. We also explored the role of intentional resources during the test phase; this manipulation is a novel contribution because previous conceptualizations of learning in AGL studies have primarily focused on the relative contribution of explicit and implicit resources to grammar learning in the acquisition phase, whereas the role of these resources during the test classification phase have gone largely unexamined. If grammar-based sources of knowledge are based primarily on intentional hypothesis testing mechanisms, for instance as would be predicted by the COVIS model of category learning, these intentional learning processes may be applied either during the acquisition phase, the test phase, or both.

In Experiment 2, we incorporated the dual-task design with the "transfer" methodology described earlier. Specifically, participants were required to do the AGL test classification task on test strings made up of an entirely new letter set. This manipulation removes the perceptual similarity between the acquisition and test phases, forcing participants to rely on knowledge that is not tied to the perceptual features of the stimuli. Adding dual-task demands to the acquisition and test phases would make intentional learning exceedingly difficult and allow us to determine whether grammar learning and the expression of such knowledge can occur automatically without the availability of perceptual features.

Experiment 1: Effects of a Working Memory Dual-Task on Standard AGL Performance

Experiment 1 was designed to address the question of whether learning in the standard AGL task can take place when intentional processing mechanisms, specifically working memory resources, are unavailable. To this end, participants were assigned to either a single-task condition or one of three dual-task conditions designed to make intentional, controlled processing very difficult. Dual-task participants were instructed to hold six digits in mind either during the acquisition phase, the test phase, or both. Assuming that our working memory task is sufficiently taxing to diminish intentional processing resources, we would expect automatic processes to prevail when the dual-task is applied. Thus, if grammaticality information primarily involves rule-based learning mediated by intentional processing in the acquisition phase, as might be suggested by the COVIS model discussed previously, we would expect individuals who receive a dual-task during acquisition to do poorly on grammaticality information. On the other hand, if rule-based learning can proceed automatically during acquisition, then the dual-task manipulation should not substantially affect the learning of grammaticality information. Similar logic applies to chunk strength learning; if chunk strength knowledge is acquired automatically during acquisition, we might expect a dual-task during acquisition to interfere minimally with chunk learning.

However, we also aim to explore the role of intentional processes in the expression of grammar and chunk knowledge. Since AGL involves both an acquisition and test phase, it is possible that some processes, such as a verbal hypothesis-testing mechanism, may occur during the test phase. It is also possible that representations learned (either automatically or otherwise) during the acquisition phase require intentional resources during the test phase for expression.

Method

Participants. Participants were 81 undergraduate students participating for course credit. They were randomly assigned to one of the following conditions: single-task (S, $N = 23$), dual-task at acquisition (DA, $N = 23$), dual-task at test (DT, $N = 19$), or dual-task at acquisition and test (DAT, $N = 16$). Of the 79 individuals reporting gender data, 44 (56%) were female. The average age was 19.1 years ($SD = 1.13$).

Materials.

Artificial grammar. The artificial grammar used in this experiment is from Knowlton and Squire (1996), which has the advantage of being a balanced chunk strength design (see Figure 1). The grammar includes 32 tests items, half of which were grammatical and half that were ungrammatical. To determine chunk strength, Knowlton and Squire (1996) quantified the similarity between learning and test items by determining the number of trigrams and bigrams in a test string that corresponded to those appearing in the learning items. Using this metric, the test items are divided into four chunk-balanced categories of eight items each: grammatical low chunk (G-LC), nongrammatical low chunk (NG-LC), grammatical high chunk (G-HC), and nongrammatical high chunk (NG-HC).

Procedure. Participants were tested individually on a computer in a small, private room. Participants in the DA condition completed a concurrent digit span task during the practice and acquisition phases, whereas those in the DT condition completed a concurrent digit span task during the test phase, as described below. Those in the S condition did not complete a dual-task. Participants in the DAT condition completed the digit span task during both the acquisition and test phases.

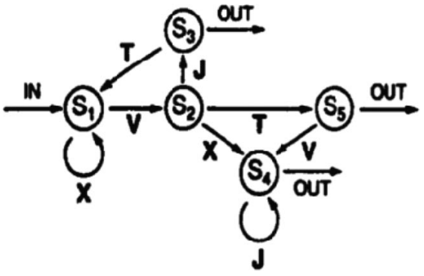

Figure 1. Balanced chunk strength grammar used in current study. Reprinted from "Artificial Grammar Learning Depends on Implicit Acquisition of Both Abstract and Exemplar-Specific Information," by B. J. Knowlton and L. R. Squire, 1996, *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22,* p. 172. Copyright 1996 by the American Psychological Association.

AGL task. The AGL task consisted of an acquisition and a testing phase. During the acquisition phase, each block began with the presentation of six random numbers (for DA and DAT participants) or asterisks (for S and DT participants) presented in the middle of the computer screen for 3,000 ms. Participants in the DA condition were instructed to maintain the number string in their memory while typing the letter strings as described below. At the end of each block, DA and DAT participants were required to type the six digits from memory, whereas S and DT participants merely had to type a number shown on the screen. All participants received eight randomly presented blocks of two or three letter strings each, where each letter string corresponded to one of the 23 training items from the artificial grammar. Participants were asked to type each letter string as shown in a space at the bottom of the screen; only after correctly typing the string were they allowed to proceed to the next trial. Participants were asked to use only one hand (their dominant hand) to type the strings.

During the testing phase, participants were informed that the letter strings shown previously conformed to very complex rules and that they should use their gut feeling to determine whether the letter strings presented next also conformed to these same underlying rules. Participants were then presented with the 32 test strings, and asked to decide whether each was grammatical or not by pressing a corresponding key on the keyboard. Similar to the dual-task during the acquisition phase, participants in the DT and DAT conditions were asked to remember six numbers while making grammaticality judgments. Prior to each block, they were shown six random numbers presented in the middle of the computer screen for 3,000 ms. Participants were instructed to maintain the number string in their memory while making three or four grammaticality judgments. At the end of each block, participants then were required to type the six digits from memory. Immediately following each grammaticality judgment, participants were asked to rate their confidence regarding the judgment they had just made on a scale of 1–4, with 1 being "I am sure" and 4 being "I am guessing." Grammaticality confidence was not obtained in the dual-task at test conditions (DT and DAT) to avoid overtaxing participants

Results and Discussion

Before describing the results on the AGL task itself, we first consider performance on the digit span dual-task. As shown in Table 1, all dual-task groups performed comparably on the digit span task, suggesting that all groups put forth equal effort on the dual-tasks. The table also shows that for the digit span dual-task, the dual-task participants correctly recalled all six digits at the end of each block between 67%–70% of the time (note that the single-task participants do not have a digit span score because they were not required to do the dual-task). This score suggests that the dual-task had the desired effect of being challenging but not impossible to do.

Next, we examine the results on the AGL task. We analyzed endorsement rates between groups using a 2 Grammaticality (Grammatical, Nongrammatical) × 2 Chunk Strength (Low, High) × 4 Condition (S, DA, DT, DAT) mixed analysis of variance (ANOVA; see Table 2 for means). As anticipated, there

Table 1
Mean (Standard Error of the Mean) Proportion Accurate on the Dual-Task During Acquisition and/or Test Across Experiments

	Experiment 1				Experiment 2		
Phase	S	DA	DT	DAT	S	DA	DT
Acquisition	—	.67 (.03)	—	.62 (.03)	—	.68 (.04)	—
Test	—	—	.71 (.07)	.75 (.05)	—	—	0.70 (.04)

Note. Dashes indicate that the dual task was not performed. S = single-task; DA = dual-task at acquisition; DT = dual-task at test; DAT = dual-task at both acquisition and test.

was a main effect of Grammaticality, $F(1, 77) = 31.37$, $p < .001$, $\eta^2_{\text{partial}} = .29$, as well as a significant Grammaticality × Condition interaction, $F(3, 77) = 4.46$, $p < .01$, $\eta^2_{\text{partial}} = .15$. G items were endorsed significantly more than NG items only for those in the S, $F(1, 77) = 24.26$, $p < .001$, $\eta^2_{\text{partial}} = .24$, and DA conditions, $F(1, 77) = 24.26$, $p < .001$, $\eta^2_{\text{partial}} = .24$ (see Figure 2). There was a trend toward higher endorsement of G compared to NG items in the DT condition, but it was not statistically significant, $F(1, 77) = 3.48$, $p = .07$, $\eta^2_{\text{partial}} = .04$. Participants in the DAT condition did not endorse G items significantly more than NG items, $F(1, 77) = .02$, $p = .89$, $\eta^2_{\text{partial}} = .00$. In contrast, Chunk Strength was learned by participants in all conditions, as demonstrated by a main effect of Chunk Strength, $F(1, 77) = 22.53$, $p < .001$, $\eta^2_{\text{partial}} = .23$, indicating that high chunk (HC) items were endorsed more often than low chunk (LC) items. These effects indicate that while participants in all conditions were able to express chunk strength knowledge, those receiving a dual-task at test (DT, DAT), struggled with expressing grammaticality information, especially when the dual-task was also at acquisition (i.e., DAT). There was also a significant Grammaticality × Chunk Strength interaction, $F(1, 77) = 27.76$, $p < .001$, $\eta^2_{\text{partial}} = .27$, such that HC items were endorsed more than LC items for NG items, $F(1, 77) = 46.67$, $p < .001$, $\eta^2_{\text{partial}} = .38$, but not for G items, $F(1, 77) = .27$, $p = .60$, $\eta^2_{\text{partial}} = .00$. Likewise, G items were endorsed significantly more than NG items for LC items, $F(1, 77) = 51.05$, $p < .001$, $\eta^2_{\text{partial}} = .40$, but not for HC items, $F(1, 77) = .23$, $p = .63$, $\eta^2_{\text{partial}} = .00$; see Table 2 for endorsement rates by condition.

In sum, the results from Experiment 1 indicate that participants completing a digit span dual-task during the acquisition phase showed a pattern of learning similar to the single-task group, suggesting that intentional processing resources are not crucial for the acquisition of either chunk or grammatical information in artificial grammar learning. However, the dual-task did appear to affect the expression of learning when it occurred during the test phase. Specifically, there was some indication that the dual-task during the test phase impaired expression of grammatical knowledge. This finding suggests that intentional resources may be more essential for grammar performance during the test phase and less essential during the acquisition phase in the standard version of AGL.

In sharp contrast, chunk strength learning was not affected by the dual-task manipulations. These results are similar to previous findings with TBI patients (Pothos & Wood, 2009), who found that patients with prefrontal damage learned chunk strength but not grammaticality information. Participants who received the dual-task at acquisition and test (DAT) in our experiment are perhaps most comparable to the TBI patients, who also had impaired working memory resources at both acquisition and test. Like Pothos and Wood (2009), we also found no expression of grammar learning when prefrontal resources were disrupted. However, we found that intentional resources were crucially important during the test phase, whereas intentional processing during the acquisition phase is not necessary for the expression of grammar learning. This may suggest that learning of grammar-based information can in fact proceed in an automatic fashion as originally hypothesized by Reber (1993) but that the expression of such knowledge is not automatic.

These findings also suggest that both the acquisition and expression of chunk strength information in AGL is mediated, at least partly, by automatic processing mechanisms, as participants demonstrated chunk strength learning even with a dual-task present at both acquisition and test.

Table 2
Mean Percentage (Standard Error of the Mean) Endorsed Grammatical Across Experiments, by Test Item Type

	Experiment 1				Experiment 2		
Variable	S	DA	DT	DAT	S	DA	DT
G-LC	63.6 (4.1)	58.2 (4.1)	69.1 (4.9)	65.6 (5.1)	64.4 (5.3)	52.1 (5.5)	65.3 (5.1)
G-HC	68.5 (3.2)	69.0 (3.2)	63.2 (4.2)	61.6 (4.8)	61.5 (4.3)	53.6 (4.5)	61.1 (4.4)
NG-LC	39.7 (4.2)	35.3 (4.2)	49.1 (4.1)	54.2 (4.8)	39.4 (3.7)	42.7 (3.8)	54.9 (4.2)
NG-HC	58.7 (3.9)	58.2 (3.9)	69.1 (4.4)	71.9 (5.0)	52.4 (4.7)	53.6 (4.9)	63.2 (4.5)
All G items	66.0 (2.6)	63.6 (2.6)	66.1 (3.6)	63.6 (3.9)	63.0 (4.1)	52.9 (4.2)	63.2 (3.7)
All NG items	49.2 (3.0)	46.7 (3.0)	59.1 (3.3)	63.0 (3.7)	45.9 (3.6)	48.2 (3.8)	59.0 (3.4)
All LC items	51.6 (3.3)	46.7 (3.3)	59.1 (3.6)	59.9 (3.9)	51.9 (3.7)	47.4 (3.9)	60.1 (3.7)
All HC items	63.6 (2.9)	63.6 (2.9)	66.1 (3.3)	66.7 (4.2)	57.0 (3.8)	53.6 (4.0)	62.2 (3.4)

Note. S = single-task; DA = dual-task at acquisition; DT = dual-task at test; DAT = dual-task at both acquisition and test; G = grammatical; NG = nongrammatical; HC = high chunk strength; LC = low chunk strength.

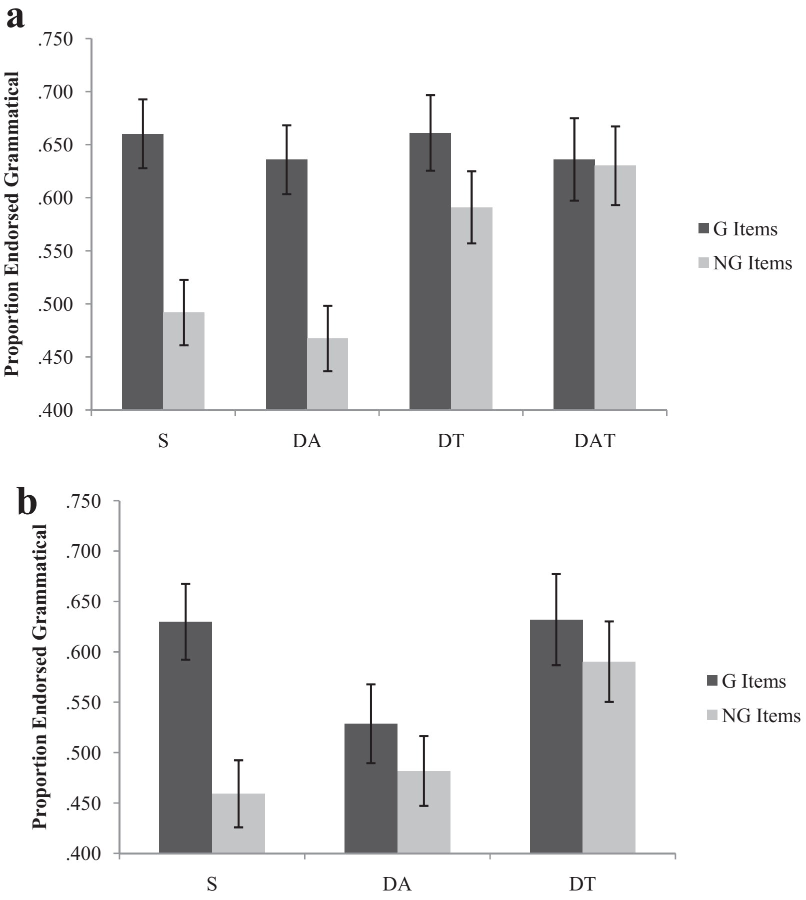

Figure 2. Proportion of grammatical (G) and nongrammatical (NG) test items endorsed grammatical in (a) Experiment 1 and (b) Experiment 2, by those in the single-task (S), dual-task at acquisition (DA), dual-task at test (DT), and the dual-task at acquisition and test (DAT, Experiment 1 only) conditions. Error bars show the standard error of the mean.

Experiment 2: Effects of a Working Memory Dual-Task on Transfer AGL Performance

In Experiment 1, we forced the dual-task participants to rely more heavily on automatic learning processes to learn both chunk and grammatical information. The results suggested that intentional processing is not crucial for learning either type of information during acquisition, since those performing a dual-task at acquisition exhibited both grammar and chunk learning similar to single-task participants. It is not clear from Experiment 1, however, what information participants in the dual-task at acquisition condition were using to correctly categorize grammatical items at test. Given that intentional learning processes, such as rehearsal and verbal hypothesis testing, were presumably disrupted by the dual-task, it is possible that they were able to use an automatic learning process, such as exemplar-based perceptual learning, to learn the grammar. The aim of Experiment 2 was to further push the limits of learning in AGL under dual-task conditions by removing an additional source of knowledge, namely, the presence of perceptual information. In order to remove the availability of exemplar-based perceptual cues, we incorporated the "transfer" methodology described earlier. Specifically, participants were required to do the test classification task on test strings that consisted of an entirely new letter set.

As discussed in the introduction, classification performance under transfer conditions is generally attenuated but still substantial. There are at least two principal theories regarding how transfer might occur, one suggesting that statistical learning of sequential dependencies forms the basis of transfer, and another suggesting episodic memory for the repetition structure of training exemplars may be sufficient. As discussed previously, Vokey and Brooks (1992) proposed that learners may use the repetition structure of sequences to form "abstract analogies" between test items and training exemplars. For example, an individual can determine that XXVXJJ and FFNFCC both derive from the same grammar because they consist of a similar pattern of repeating elements.

Nonetheless, transfer has also been shown to occur even when there are no repeating elements within a grammar (Dienes, Altmann, & Gao, 1999; Tunney & Altmann, 2001). Dienes et al. (1999) accurately simulated transfer performance using a modified simple recurrent network model that can learn sequential dependencies between repeating and nonrepeating elements and apply those to a new vocabulary. Rather than storing fragments or whole exemplars, the model utilizes a statistical learning process to encode the relationship between elements. In comparing the statistical learning model of Dienes et al. (1999) to the abstract analogies model, Tunney and Altmann (2001) found that both contribute to transfer performance under different circumstances: Abstract analogies accounted for transfer when there was repetition between elements, and statistical learning accounted for transfer when no repetition was present.

Returning to the present study, we investigate how well the dual-task participants will perform on the transfer task, given that they can only rely on automatic sources of knowledge that are not tied to the perceptual features of the stimuli. According to previous research, transfer performance is dependent on the learning of either abstract analogies or sequential dependencies. Given that abstract analogies rely upon episodic memory for the repetition structure of the exemplars, we might expect that this process is more dependent on intentional processes. Under this view, intentional processes might be necessary both during acquisition to encode the repeating elements and also during test to retrieve those elements and apply them to the test string at hand. Indeed, Casale, Roeder, and Ashby (2012) found almost perfect analogical transfer in rule-based tasks believed to rely heavily on explicit hypothesis-testing, and no evidence of analogical transfer in implicit information-integration tasks. Given the presumed reliance on intentional processing, we might expect a dual-task to severely impair transfer performance to the extent that it relies upon abstract analogy learning. On the other hand, unlike abstract analogies, the learning of sequential dependencies relies on statistical learning, a type of learning that is thought to proceed relatively automatically. Thus, the extent to which dual-task participants can use statistical learning to learn the sequential dependencies between stimuli and apply such knowledge at test, then we would expect transfer performance to remain high under dual-task conditions.

Given that DAT participants in Experiment 1 failed to learn when perceptual information was available, we reasoned that learning in a DAT condition without the availability of perceptual cues would be highly unlikely. Therefore, we only retained the S, DA, and DT conditions in Experiment 2. We predicted that single-task participants, who have intentional processes still available, would show some learning even without perceptual-based cues, especially given the previous studies demonstrating successful transfer performance (e.g., Tunney & Altmann, 2001). For dual-task participants, however, we expect that grammar learning will be much more attenuated, especially when intentional processing is disrupted during test.

Method

Participants. Participants were 68 undergraduate students participating for course credit. They were randomly assigned to one of three conditions: single-task (S, $N = 26$), dual-task at acquisition (DA, $N = 24$), or dual-task at test (DT, $N = 18$). Of the 66 participants reporting gender data, 42 (58%) were female. The sample had an average age of 19.7 ($SD = 3.0$, $N = 67$).

Materials and procedure. The materials and procedure for the single and dual-task groups were identical to Experiment 1, with the exception that the test strings used letters F, Z, N, and C in place of X, T, V and J, respectively. The replacement letters were chosen to be perceptually dissimilar from the acquisition letters, and vowels were avoided so that words could not be formed from strings. Care was also taken to ensure that the letters used for test strings did not result in common acronyms that could affect the expression of learning.

Results and Discussion

As Table 1 shows, performance on the digit span in the dual-task conditions was similar to Experiment 1. Once again, we analyzed endorsement rates between groups using a 2 Grammaticality (Grammatical, Nongrammatical) × 2 Chunk Strength (Low, High) × 3 Condition (S, DA, DT) mixed ANOVA (mean endorsement rates are found in Table 2). Overall, there was a main effect of both Grammaticality, $F(1, 65) = 17.11$, $p < .001$, $\eta^2_{\text{partial}} = .21$, and Chunk Strength, $F(1, 65) = 5.10$, $p < .05$, $\eta^2_{\text{partial}} = .07$, as well as a significant interaction between Grammaticality and Chunk Strength, $F(1, 65) = 8.54$, $p < .01$, $\eta^2_{\text{partial}} = .12$. Similar to Experiment 1, HC items were endorsed more than LC items for NG items, $F(1, 65) = 15.98$, $p < .001$, $\eta^2_{\text{partial}} = .20$, but there was no significant difference in endorsement rates for LC and HC items for G items, $F(1, 65) = .34$, $p = .56$, $\eta^2_{\text{partial}} = .01$. Further, G items were endorsed more than NG items for LC, $F(1, 65) = 24.31$, $p < .001$, $\eta^2_{\text{partial}} = .27$, but not HC, $F(1, 65) = .63$, $p = .43$, $\eta^2_{\text{partial}} = .01$, items. Finally, there was a significant interaction between Condition and Grammaticality, $F(1, 65) = 4.41$, $p < .05$, $\eta^2_{\text{partial}} = .12$. Follow-up tests indicated that G items were endorsed more than NG items for participants in the S condition, $F(1, 65) = 26.17$, $p < .001$, $\eta^2_{\text{partial}} = .29$, but not the DA, $F(1, 65) = 1.82$, $p = .18$, $\eta^2_{\text{partial}} = .03$, or the DT, $F(1, 65) = 1.08$, $p = .30$, $\eta^2_{\text{partial}} = .02$, conditions, suggesting that only the single-task group could both acquire and express grammaticality knowledge (see Figure 2). There was no interaction of Condition with Chunk Strength, suggesting that the three groups did not differ in learning of chunks.

Unlike Experiment 1, these findings suggest that the dual-task manipulation affected learning regardless of whether it took place at acquisition or test. Without explicit processing resources available, and when the perceptual features of the stimuli change at test, very little, if any, grammar-based knowledge is demonstrated. Thus it appears that intentional processing may be a primary pathway to grammar learning in AGL transfer experiments. Given that our stimuli utilize a number of repeating elements and that repeating and nonrepeating sequential dependencies are somewhat controlled by the balanced chunk strength design, the abstract analogies approach of Vokey and Brooks (1992) may have predominated for learners in our task. Since abstract analogies are reliant on episodic memory formation during acquisition, it is likely that our dual-task inhibited both the acquisition and retrieval of information necessary to apply the abstract analogies approach. It is possible that the statistical learning process suggested by Dienes et al. (1991) would result in learning for dual-task participants when stimuli contain no repeating elements.

In summary, Experiment 1 demonstrated that artificial grammar learning takes place more or less equivalently even when explicit processing resources are reduced during the acquisition phase. On the other hand, Experiment 2 showed that removing access to intentional processing resources during acquisition disrupts learning if perceptual cues are also made unavailable at test (using transfer methodology). However, when intentional processing resources were disrupted during test, disruptions in the expression of grammaticality knowledge occurred for both standard and transfer AGL tasks, suggesting that intentional processing resources are crucial for the expression of grammar learning in AGL.

General Discussion

The goal of this study was to dissociate automatic and nonautomatic forms of learning in AGL by using dual-task methodology. In Experiment 1, a digit span dual-task was used during AGL acquisition and during test to diminish intentional learning. Participants who were required to perform a dual-task during the acquisition phase showed strikingly similar test classification performance to the single-task control group. Thus, even when intentional processing resources are unavailable during the acquisition phase, learning of grammatical information can still occur, suggesting that automatic encoding processes may be at play. These automatic encoding processes appear to be sufficient for achieving comparable performance levels, as long as intentional processing resources are available during the test phase. On the other hand, when the dual-task occurred during the test phase, the expression of grammatical-based knowledge, but not chunk information, was attenuated. This suggests that while the acquisition of both grammar-based and chunk information can be relatively automatic, the expression of these two types of knowledge require different levels of intentional resources.

In Experiment 2, we clarified the nature of the automatic encoding processes implicated in Experiment 1, using transfer methodology to remove perceptual information. Without access to either intentional processes during acquisition or perceptual cues at test, very little grammar learning took place. These results thus may indicate that the primary mode of automatic learning that is available in the encoding phase is a perceptual fluency process. For instance, it has been previously suggested that implicit statistical learning processes might be akin to a type of perceptual learning (Conway, Goldstone, & Christiansen, 2007), with learning of regularities being based largely on perceptual-based, modality-specific mechanisms (Emberson, Conway, & Christiansen, 2011). Our present results are also consistent with recent proposals that automatic knowledge is acquired primarily through exemplar-based perceptual mechanisms (Chang & Knowlton, 2004). Although perceptual fluency is one candidate for this exemplar-based perceptual process, the specific nature of the perceptual process cannot be determined from the present findings.

Both experiments provide evidence that intentional processing resources during the classification test phase are especially crucial. When intentional processing is disrupted during test by a concurrent memory load, participants performing either a standard or a transfer AGL task showed attenuated grammar knowledge expression. Thus, whereas intentional processing resources only appear to be needed during the acquisition phase when the task involves transfer, it is relatively clear that intentional processing resources are relied upon quite heavily during the test phase, regardless of whether the task involves transfer or not. Perhaps this is not surprising since the classification task itself is a direct test, explicitly asking participants to make a conscious decision about the test strings. Perhaps under different test conditions that are more indirect (e.g., reaction times), engaging in a dual-task at test might not have as great an effect. An example of such a phenomenon occurs in the mere exposure effect, where exposure to a stimulus can result in higher ratings of pleasantness (an indirect measure of memory) without influencing recognition judgments (a more direct measure; see Whittlesea & Rice, 2001). Likewise, perhaps grammar knowledge could have been demonstrated in the dual-task at test conditions using an indirect test.

The differential effects of intentional resources on the expression of grammar versus chunk information are somewhat consistent with a recent study examining TBI patients (Pothos & Wood, 2009). The study demonstrated that TBI patients, who have impaired intentional processing resources due to prefrontal lobe damage, fail to learn grammaticality information, but not chunk strength information, in the standard AGL task. Notably, however, the use of TBI patients made it impossible for Pothos and Wood (2009) to separate the effects of prefrontal damage on the learning and test phases of AGL; patients were impaired during both phases. Our study clarifies the relationship between prefrontal processes and the training and test phases in AGL. Specifically, intentional processing does not appear necessary for encoding grammar-based or chunk-based sources of knowledge in AGL, but intentional processing is crucial for the expression of grammar-based knowledge.

Pothos and Wood (2009) argued that their results are consistent with the COVIS (Ashby & Maddox, 2005) model of category learning. The COVIS model theorizes separate implicit and explicit category learning systems with distinct neuropsychological substrates. In addition to a verbal hypothesis-testing system for rule-based data, the model also posits the existence of an implicit information-integration system. The hypothesis-testing system derives explicit verbal rules from data, relying heavily on brain structures involved with working memory and visual attention, such as the prefrontal cortex, anterior cingulate, and the head of the caudate nucleus (Ashby, Alfonso-Reese, Turken, & Waldron, 1998). Information-integration is hypothesized to be a perceptual process that involves the integration of two or more stimulus dimensions, and relies on subcortical structures such as the tail of the caudate nucleus (Ashby et al., 1998; Ashby & Maddox, 2005). Evidence from Pothos and Wood (2009) suggested that rule-based information is preferentially affected by prefrontal damage, and thus may implicate the verbal hypothesis-testing system predicted by COVIS. Our results are not entirely consistent with the predictions of COVIS; if the learning of rule-based grammar information is based entirely on prefrontal-based hypothesis-testing mechanisms, we would expect attenuated grammar knowledge when a dual-task is performed concurrent with either the acquisition phase or test phase (or both). Instead, we found grammar-based learning was unimpaired with a dual-task at acquisition. In an attempt to reconcile the contrasting findings, it is possible that the process of verbal hypothesis testing is applied only during the test phase, which would explain why our dual-task at acquisition participants still showed grammar learning.

Additional support for the idea that a verbal hypothesis testing system may contribute to the expression of grammar knowledge during AGL comes from evidence that learners develop microrules (Dulany et al., 1984) to explain the grammaticality of acquisition items and that the verbal rules learners produce can subsequently be used by yoked participants successfully to categorize test stimuli (Mathews et al., 1989). Further support comes from a transcranial direct current stimulation (tDCS) study by de Vries et al.

(2010). Using stimuli controlling for cues of superficial similarity, they found that tDCS stimulation of Broca's area improved grammaticality performance, providing support for the idea that grammaticality performance is based primarily on the development of verbal rules. Finally, there is some evidence that areas involved in the procedural and hypothesis-testing systems in COVIS are implicated in AGL. Lieberman, Chang, Chiao, Bookheimer, and Knowlton (2004) conducted an fMRI study of AGL performance using a balanced chunk strength grammar identical to the one used in the current study. They found that when controlling for chunk strength information, the head of the caudate nucleus was active during grammaticality judgments. This is consistent with the predictions of COVIS, which suggest that explicit rule-based information involves a frontal-striatal circuit that includes the head of the caudate (Ashby & Maddox, 2005).

Chunk strength learning, on the other hand, appears to be largely based on a perceptual exemplar-based process and may involve the information-integration system postulated by COVIS. Nonetheless, research discussed in the introduction also suggests that chunk strength knowledge may also involve explicit item memory for chunks. Future research might clarify these apparent discrepancies and determine to what extent the systems postulated by COVIS actually apply to the learning of grammar-based and chunk strength information in AGL.

A number of limitations of the current study should be noted. First, although we attempted to control for item similarities between test items and training exemplars using a balanced chunk strength design, we did not attempt to control for aspects of item similarity unrelated to chunk strength, such as the abstract analogy approach suggested by Vokey and Higham (1992). Some studies have shown that the specific similarity effect (that arises from abstract analogies) disappears when chunk strength is considered (Knowlton & Squire, 1994), but others have found independent effects of both specific similarity and chunk strength (e.g., Higham, 1997). Second, it could also be argued that our dual-task may have impaired resources necessary for automatic processing as well as those for intentional forms of processing. However, we did ask participants to type the strings (with one hand) while remembering the digits, thus ensuring that some minimal attention was applied to the letter strings. Given that our dual-task at acquisition participants learned the grammar similarly to those in the single task condition, we can assume that the attention required for automatic processing was present. Third, we cannot be absolutely certain that the dual-task we employed diminished intentional processing to the desired degree. The working memory task was not calibrated for each individual subject (it was set at six items for everyone), so it is possible that participants with high working memory were not sufficiently taxed. On the other hand, the fact that we did observe effects in some dual-task conditions suggests that the task was taxing intentional resources to some degree. However, a replication of the current study would be strengthened by the use of a dual-task calibrated for the participants' ability level and a control condition to ensure that the task is achieving the desired effect. Fourth, we used a very simple finite state grammar that may have encouraged the development of explicit knowledge; it is possible that using more complex patterns might involve the use of automatic versus nonautomatic processes to different degrees. Finally, the present stimulus materials have been frequently employed in the AGL literature (Chang & Knowlton, 2004). Although the reuse of stimulus materials allows for easier between-study comparisons, it may also confound study results by replicating biases present in the original grammar[1] (Jiménez, 2011). Replication of the present results with a grammar carefully controlled for biases would allow firmer conclusions about the automaticity of AGL (or lack thereof).

In summary, these results suggest that to some extent learning in AGL tasks is indeed automatic: both chunk and grammar-based learning can occur when a dual-task is used during the acquisition phase. On the other hand, the expression of grammatical knowledge, but not chunk information, does appear to depend on intentional processing resources. Finally, when perceptual similarity of the test items is not available, then explicit processing resources are needed during the acquisition phase as well, presumably in order to encode the more abstract structural relations among the stimuli that can then be used to correctly classify novel grammat-

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[1] Reviewers of an earlier version of this article raised concerns about possible biases in our stimulus materials that are uncontrolled. It is possible that what we refer to as "grammar learning" is nothing more than the learning of chunks larger than bigrams or trigrams (e.g., fragments of lengths four, five, or six), which is not controlled for in the measure of chunk strength. To address this concern, we calculated the chunk strength of test items for chunks four, five, and six items long, which we call "large" chunk strength (LCS). The results of a Mann-Whitney test indicated that LCS was larger for G items than NG items ($z = -2.39$, $p < .05$, mean rank G items = 16.9, mean rank NG items = 10.2). However, we found that three items in particular were influencing the LCS for G items. We removed those three items and redid the analyses of Experiment 1. After removal of those items, G and NG items no longer differed significantly on LCS ($z = -1.85$, $p = .10$) and the LCS means for G and NG items were comparable (G items $M = 0.58$, $SD = 0.60$; NG items $M = 0.53$, $SD = 1.42$). The reanalysis of Experiment 1 indicated that, just as with the original findings, there was a main effect of Grammaticality, $F(1, 77) = 29.21$, $p < .001$, as well as a significant Grammaticality × Condition interaction, $F(1, 77) = 2.92$, $p < .05$. Both S and DA participants demonstrated learning of grammaticality information (ps < .001), whereas G and NG test item endorsements were not significantly different for the DT ($p = .10$) and DAT ($p = .49$) conditions. Therefore, we conclude that LCS does not explain our grammar-learning results. Another concern raised by reviewers was that our demonstration of chunk learning in the DT and DAT conditions may have been unduly influenced by NG items with NG transitions at the last two positions of the string. The reasoning was that DT and DAT participants may have been too distracted to reach the end of the string. To address this criticism, we ran new analyses that excluded items in which the nongrammatical transition was at the end of the string (either in the last transition or second-to-last transition). When those nine items were removed, the chunk strength of NG-HC items was 8.8 (compared to 8.6 for all items) and the chunk strength of NG-LC items was 5.7 (compared to 5.4 for all items). When we reran the ANOVA from Experiment 1, the main effect of Chunk Strength, $F(1, 77) = 4.70$, $p < .05$, remained, but there was also a significant Grammar × Condition × Chunk Strength interaction, $F(3, 77) = 3.25$, $p < .05$. Pairwise comparisons indicated that removing those items eroded chunk strength learning for NG items for all conditions except the DT condition. In contrast to the original findings, those in the S ($p = .41$), DA ($p = .89$), and DAT ($p = .14$) conditions did not demonstrate significant chunk learning for NG items. Individuals in the DT condition, however, still endorsed NG-HC items more than NG-LC items ($p < .05$). Given that the DT condition retained chunk learning for NG items after removal of those with transitions at the end, we can conclude that NG transitions at the end of a string cannot explain chunk learning for DT participants. It is interesting that chunk learning for NG items in other conditions degraded after removal of those items, but it is notable that the main effect of chunk strength remained. Thus, even after removing NG items with transitions at the end of the string, overall chunk strength learning remained, though it was degraded in the subset of NG items for most conditions.

ical patterns at test. These results to some extent are consistent with the COVIS model, which postulates the existence of an explicit (intentional) hypothesis-testing system and an implicit (automatic) information-integration system. However, rather than merely two learning routes, our findings are more consistent with the existence of at least three relatively independent learning mechanisms operating in parallel: (a) an automatic grammar-based learning mechanism that requires attentional resources only when making classification judgments, (b) an automatic chunk-based learning mechanism that does not require attentional resources to make classification judgments, (c) and an explicit hypothesis-testing system that is needed to learn grammar-based regularities among stimuli when perceptual similarity is removed. Our findings thus highlight the importance of distinguishing between processing mechanisms at acquisition versus at test, a distinction that is not often made in the AGL literature. To conclude, we suggest that future work take into account processes operating at both the acquisition and test phases of AGL and that it may prove fruitful to design neuroimaging studies to specifically isolate the underlying neural circuits involved at each phase.

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