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Implicit learning and implicit treatment outcomes in individuals with aphasia

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Abstract

Background—Implicit learning is a process of learning that occurs outside of conscious awareness and may be involved in implicit, exposure-based language training. However, research shows that implicit learning abilities are variable among individuals with aphasia, and it remains unknown whether individuals who show basic implicit learning abilities also benefit from implicit language training.

Aims—The aims of this series of experiments were to test implicit learning in individuals with agrammatic aphasia, examine the effects of a novel implicit language treatment, and investigate whether individuals with aphasia who show implicit learning ability also benefit from implicit treatment focused on passive sentence comprehension.

Methods & Procedures—Nine participants with chronic agrammatic aphasia and 21 neurologically intact participants completed a visuomotor serial reaction time test of implicit learning (Experiment 1). The participants with aphasia also completed a short-term novel implicit sentence comprehension treatment (Experiment 2) that consisted of five sessions of repeated exposure to grammatically correct passive sentences and matching photographs. Sentence comprehension was tested in multiple baseline sessions and on each day of training using a sentence-picture matching task. The relation between participants' learning patterns across experiments was also examined.

Outcomes & Results—Individuals with agrammatic aphasia as well as neurologically intact adults demonstrated significant implicit sequence learning in the serial reaction time task. However, the participants with aphasia did not show concomitant improvement in sentence comprehension as a result of the implicit treatment protocol.

Conclusions—This study suggests that individuals with agrammatic aphasia demonstrate implicit learning ability; however, this ability does not necessarily promote successful outcomes in treatment that is based solely on implicit training methods.

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Keywords

agrammatic aphasia; implicit learning; implicit treatment; serial reaction time task; sentence comprehension

Introduction

Although treatment for aphasia often involves both explicit instruction and implicit language exposure and practice, some interventions have been designed to emphasize the implicit aspects of training. “Implicit treatment” typically refers to exposure-based training and the absence of explicit instruction in intervention, such as the use of errorless learning (Fillingham, Hodgson, Sage, & Lambon Ralph, 2003) and masked repetition priming (Silkes, Dierkes, & Kendall, 2013) for the treatment of anomia as well as certain types of conversation therapy in which clinicians mediate interactions without providing explicit instructions in target behaviors (Simmons-Mackie, Savage, & Worrall, 2014). In contrast, “implicit learning” refers to a process of learning that occurs outside of conscious awareness, as demonstrated in experimental paradigms like artificial grammar learning (Reber, 1967) and the serial reaction time task (Nissen & Bullemer, 1987). Although implicit learning abilities may be relevant to the efficacy of implicit language training, no study to our knowledge has examined implicit learning and implicit treatment in the same group of individuals with aphasia. In the present study, we conducted a series of experiments to test implicit learning in agrammatic aphasia, examine the effects of a novel implicit language treatment, and investigate whether individuals with aphasia who show implicit learning ability also benefit from implicit treatment.

Implicit learning in aphasia

Research suggests that individuals with agrammatic aphasia show some ability to learn novel information under implicit conditions, but implicit learning abilities in this population are variable across individuals and across different types of tasks. People with agrammatic aphasia have shown implicit learning of sequences in serial reaction time tasks (Goschke, Friederici, Kotz, & van Kampen, 2001; Schuchard & Thompson, 2014), but have also exhibited impairments in learning certain types of sequences (Goschke et al., 2001) and in learning the abstract underlying structures of sequences (Dominey, Hoen, Blanc, & Lelekov-Boissard, 2003). Additionally, a study that used a visual artificial grammar showed implicit learning deficits associated with agrammatic aphasia (Christiansen, Kelly, Shillcock, & Greenfield, 2010). However, a separate visual artificial grammar study in which the results were analyzed at an individual level suggested that the extent and types of learning impairment are highly heterogeneous among individuals with aphasia (Zimmerer, Cowell, & Varley, 2014), and a recent study showed evidence of exposure-based artificial grammar learning in the verbal domain in people with agrammatic aphasia (Schuchard & Thompson, in preparation). If implicit learning processes are engaged in implicit treatment approaches, then the individual differences in implicit learning abilities that have been demonstrated in prior research may affect the outcomes of treatment. However, the present study is the first to our knowledge to examine both implicit learning abilities and implicit treatment outcomes in a group of individuals with aphasia.

In Experiment 1, we used a visuomotor serial reaction time task (SRTT) to test implicit learning in individuals with aphasia and neurologically intact adults. This task was selected because it is a well-established implicit learning paradigm that does not require linguistic processing or production, and hence the language impairments of the participants with aphasia should not preclude their ability to complete the task. Moreover, the SRTT has been used in previous research to reveal relationships between learning and language processes. Although the repeating sequences that participants learn in the SRTT are much simpler in structure than the grammatical rules of language, the ability to acquire simple patterns in sequence learning tasks is associated with language processing skills, particularly the ability to predict upcoming words in sentences (Conway, Bauernschmidt, Huang, & Pisoni, 2010; Dominey et al., 2003; Misyak, Christiansen, & Tomblin, 2010). The visuomotor SRTT has also been used to identify learning impairments associated with language disorders, including specific language impairment (Hedenius et al., 2011; Lum, Conti-Ramsden, Page, & Ullman, 2012; Tomblin, Mainela-Arnold, & Zhang, 2007) and dyslexia (Howard, Howard, Japikse, & Eden, 2006; Menghini, Hagberg, Caltagirone, Petrosini, & Vicari, 2006; Vicari et al., 2005). However, it is not yet known whether individuals with aphasia who demonstrate basic implicit learning abilities in tasks like the SRTT also benefit from implicit language training, and conversely whether those who demonstrate deficits in implicit learning show less benefit from implicit language training.

Implicit treatment for aphasia

Of the implicit interventions that have been developed for aphasia, the approach most relevant to the present study is that of errorless learning. The repetitive exposure-based methods of errorless learning closely resemble the methods of implicit learning and memory tasks, although explicit memory may also be involved in errorless learning interventions (Fillingham et al., 2003; Squires, Hunkin, & Parkin, 1997). Theories of errorless learning are based on the Hebbian learning principle that when neurons fire together, the strength of the connections between them increases (Hebb, 1949). This principle suggests that making a particular response to a particular stimulus strengthens that association, whether or not the response is correct. Therefore, errorless learning interventions were developed to eliminate opportunities to make errors, which putatively reinforce incorrect responses. In treatments that use errorless learning to address word-finding difficulties in aphasia, the patient typically hears and/or views the name of an object or action paired with a matching picture and repeats the name, with multiple repetitions per item (Conroy, Sage, & Lambon Ralph, 2009; Fillingham, Sage, & Lambon Ralph, 2005a; 2005b; 2006; McKissock & Ward, 2007).

In Experiment 2, we examined a novel implicit language treatment that applies principles of errorless learning to sentence comprehension training. The treatment was designed to be implicit with respect to both participant instructions and training methods. Participants did not receive explicit instruction in the sentence structure that was being trained, nor were they taught to use any particular strategy during training. Training sessions consisted of repeated exposures to grammatically correct sentences and matching pictures, with no opportunities for overt errors because participants were not asked to answer comprehension questions during training. Passive sentences were used as training stimuli because individuals with agrammatic aphasia often have difficulty comprehending syntactically complex sentences, including passives (e.g., Caplan & Futter, 1986; Grodzinsky, Pinango, Zurif, & Drai, 1999; Meyer, Mack, & Thompson, 2012; Schwartz, Saffran, & Marin, 1980).

This study was designed to examine whether people with agrammatic aphasia demonstrate nonverbal implicit sequence learning abilities, whether they benefit from an implicit approach to sentence comprehension treatment, and whether performance on the implicit learning task reflects implicit treatment outcomes. Participants with aphasia and neurologically intact age-matched control participants completed the SRTT (Experiment 1). Following baseline assessment of sentence comprehension, participants with aphasia also completed one of two implicit passive sentence comprehension treatment protocols: an initial protocol of implicit treatment (Experiment 2a) or a revised protocol that addressed issues revealed during testing of the first version (Experiment 2b). We predicted that people with aphasia would demonstrate implicit sequence learning on the SRTT, similar to the performance of age-matched control participants, and that individual differences in performance on the SRTT may be associated with individual differences in implicit sentence comprehension treatment outcomes.

Experiment 1. Serial reaction time task (SRTT)

Introduction

The purpose of Experiment 1 was to test implicit learning abilities in individuals with aphasia and neurologically intact age-matched adults. Implicit learning was tested using the serial reaction time task (SRTT), a well-established visuomotor sequence learning paradigm.

Methods

Participants—Participants included 9 adults with chronic agrammatic aphasia resulting from a single left hemisphere stroke (4 male; age 35-65, M=49). Table 1 provides descriptions of the participants with aphasia. This experiment also included 21 neurologically intact adults (11 male; age 32-65, M=55) who completed the SRTT as part of a larger cognitive testing battery. The neurologically intact adults were not significantly different from the participants with aphasia in age, $t(17.6)=1.61$, p=.13, or years of education, $t(13.2)=0.22$, p=.83. All participants were monolingual English speakers who reported having normal or corrected-to-normal vision and hearing and no history of learning disorders or language disorders other than aphasia. Participants provided written informed consent approved by the Northwestern University Institutional Review Board.

All participants with aphasia completed assessments of language production and comprehension (see Table 2). Language testing included the *Western Aphasia Battery-Revised* (WAB-R; Kertesz, 2007), the *Northwestern Assessment of Verbs and Sentences* (NAVS; Thompson, 2011), and speech samples collected by asking participants to tell the story of Cinderella. Speech samples were recorded, transcribed, and analyzed to provide measures of speech production including the percentage of grammatically correct sentences and average words per minute. Inclusionary criteria for this study included symptoms consistent with agrammatism, such as nonfluent speech and greater difficulty producing and comprehending noncanonical compared to canonical sentence structures.

Stimuli and procedures—At the beginning of the task, participants were seated in front of a Lenovo ThinkCentre computer and asked to rest four fingers on four buttons of a Cedrus RB response pad, using whichever hand was more comfortable for them. In each trial of the SRTT, an asterisk appeared in one of four squares displayed horizontally on the computer monitor. The asterisk remained until the participant pressed the response pad button corresponding with the location of the asterisk. The interstimulus interval was 400 ms. The task included sequenced trials, in which the asterisk appeared in the order of the following repeating 12-item sequence of locations: 2-3-1-4-3-2-4-1-3-4-2-1, with 1 corresponding to the left-most square and 4 corresponding to the right-most square. Prior to and following the sequenced trials, the task also included blocks of randomly ordered trials, in which the asterisk appeared in randomly determined locations, with the conditions that all four positions occurred with equal frequency and no immediate repetitions (e.g., 1-2-2). Specifically, participants first completed 60 randomly ordered trials to become acquainted with the task, followed by 300 sequenced trials. Finally, participants completed an additional 60 randomly ordered trials to assess changes in response time that could reflect implicit learning of the sequence during the preceding 300 trials, for a total of 420 trials that required 5-10 minutes to complete (modeled after Brown, Robertson, & Press, 2009). These blocks of random and sequenced trials were administered as a single continuous task without breaks. Stimuli were presented using SuperLab software (Cedrus, Phoenix, Arizona).

Importantly, participants were not informed that there would be an underlying pattern in the stimuli. Their task was simply to push the button on the response pad that corresponded to the asterisk's location on the monitor as quickly and accurately as they could. Implicit sequence learning in this paradigm is indicated by significantly higher reaction times during the final random block compared to the immediately preceding sequenced block of trials, which demonstrates that task performance is disrupted when the implicitly practiced sequence is no longer present.

Data analysis—The first ten trials of the initial randomly ordered block were considered practice trials and were removed prior to analyses, whereas the remaining 50 trials in the initial randomly ordered block were included to provide a measure of baseline reaction time prior to the introduction of sequenced trials. Incorrect trials were also removed from reaction time (RT) analyses. Outliers in RT were eliminated by removing trials in which the RT was more than three standard deviations above or below the overall mean RT of the participant's session. The RT value for each trial was then converted to a z-score, indicating how many standard deviations the value fell above or below the participant's overall mean RT. Although the task was administered without breaks, for the purposes of data graphing and analysis, RT data were averaged within the following seven blocks: the initial block of 50 random trials (Block 1), followed by five blocks of 60 sequenced trials each (Blocks 2-6), and finally a block of 60 random trials (Block 7). The alpha level for all statistical tests was 0.05.

Results

Accuracy in the SRTT was close to ceiling in both participant groups. Individual mean accuracy ranged from 86% to 100% (M=96.9%) among neurologically intact adults and from 92.7% to 99.5% (*M*=96.5%) among individuals with aphasia. Group mean accuracy remained above 93% across the seven blocks of the task in both groups (see Figure 1b).

Individual mean RT in the SRTT ranged from 356 ms to 744 ms (*M*=518 ms) among neurologically intact adults and from 377 ms to 910 ms (*M*=633 ms) among individuals with aphasia. Due to the high variability in raw RT across participants, the following statistical analyses used the RT data that was standardized using z-score conversions (see Figure 1a). A 2 (group: aphasia vs. neurologically intact) by 2 (block: Block 6 vs. Block 7) mixed ANOVA revealed a significant effect of block, $F(1,28)=22.84$, $p<.001$, indicating slower RT in the random Block 7 compared to the sequenced Block 6. There was no significant effect of group, $F(1,28)=0.49$, $p=.49$, or group by block interaction, $F(1,28)=2.75$, $p=.11$. Notably, the group of individuals with aphasia was smaller than the group of neurologically intact adults, but dependent t-tests confirmed that a significant increase in RT between Block 6 and Block 7 was observed in the group of individuals with aphasia, $t(8)=2.67$, $p=.03$, as well as in the group of neurologically intact adults, $t(20)=5.36$, $p<.001$. Within these groups, 18/21 neurologically intact participants and 7/9 participants with aphasia showed an increase in RT (>5 ms) between Block 6 and Block 7, with two participants with aphasia (P3 and P7) showing very small decreases in RT (<5 ms) between these blocks.

Discussion

The primary indication of implicit sequence learning in the SRTT is slower reaction time in the final random block compared to the immediately preceding sequenced block, indicating that task performance is disrupted when the practiced sequence is no longer present, even though participants are not informed of the underlying sequence. In the present experiment, this implicit learning effect was observed in the group of individuals with aphasia as well as the group of neurologically intact adults. At an individual level, it is difficult to determine whether a single participant’s increase in reaction time in the final random block should be attributed to implicit learning or to random variation. However, it is notable that the group-level effects were not driven by only a few individuals. Rather, 18/21 neurologically intact adults and 7/9 individuals with aphasia showed a reaction time increase in the final random block.

Experiment 2a. Implicit sentence comprehension treatment

Introduction

The purpose of Experiment 2a was to examine a novel implicit approach to auditory sentence comprehension training for people with aphasia. Training consisted of five sessions of repeated exposures to passive sentences and matching photographs, and learning was assessed using a sentence-picture matching test.

Methods

Participants—Five of the individuals with aphasia who participated in Experiment 1 (P1-P5) served as participants for this experiment. Participant descriptions and language testing data for these individuals are summarized in Tables 1 and 2. The participants demonstrated mild impairments in comprehension on the WAB Auditory Verbal Comprehension subtest, ranging in score from 7 to 9.3 out of 10 (*M*=8.0). Three of the five participants showed greater difficulty comprehending noncanonical compared to canonical sentence structures on the NAVS Sentence Comprehension Test, and four of the five participants showed impairments in comprehending passive sentences (*M*=68% correct). P3 scored 100% correct on the NAVS passive sentences but showed impairments in comprehending passive sentences during baseline testing.

Design—This experiment used a single-subject multiple baseline design across participants. Baseline sentence comprehension testing was administered 2-4 times prior to the start of training. Training consisted of five sessions for all participants, administered between 3 and 5 consecutive days. Due to participants' scheduling constraints, P1 and P2 completed sessions 1 and 2 on the first day, sessions 3 and 4 on the next day, and session 5 on the third day, with the same-day sessions separated by at least three hours. P3, P4, and P5 completed the five sessions of training on five consecutive days. To assess performance across the five sessions, each training session was immediately followed by administration of the same sentence comprehension test used during baseline testing.

Stimuli and procedures

Testing: The sentence comprehension test included 20 semantically reversible passive sentences with a by phrase and an adjunct clause, each with a different verb (see Appendix A). The verbs used in 10 of the test sentences were also included in training sentences, whereas the other 10 verbs in the test sentences were untrained. The test sentences were recorded by a male native English speaker at a rate of approximately 3.5 words per second. Each sentence was paired with a line drawing depicting the correct meaning of the sentence and a second line drawing depicting the meaning of the sentence when the roles of the participants were reversed. For example, the sentence *The dog was followed by the cat in the woods* was paired with a picture of a cat following a dog and a picture of a dog following a cat.

The sentence comprehension test used a computerized sentence-picture matching task. Participants were instructed to listen to each sentence and then press a key indicating whether the picture presented on the left or the right side of the monitor matched the sentence. Each trial began with a 2000 ms fixation cross followed by the simultaneous presentation of an auditory sentence and the two corresponding pictures displayed side-by-side on the monitor. The pictures were displayed until the participant responded or until eight seconds after the end of the sentence if the participant did not respond in that time.

Training: Training stimuli included 50 passive sentences with a by phrase and an adjunct clause, each with a different verb (see Appendix B). Seventeen of the sentences were semantically reversible and 33 were irreversible. Photographs depicting each of the 50 sentences were selected from free online sources. To help maintain attention during the training task, 15 of the sentence/picture pairs were associated with a yes/no question about a person or object in the picture that was unrelated to the relation between the agent and theme in the passive sentence. The training sentences and questions were recorded by a female native English speaker at a rate of approximately 2.5 words per second.

In each computerized training session, the set of 50 passive sentences and their corresponding pictures were presented in a random order three times, for a total of 150 trials without breaks lasting approximately 20 minutes. Participants were instructed to listen to the sentences and view the matching pictures. In each trial, the picture appeared for 500 ms before the auditory presentation of the sentence began, and it remained for 1000 ms after the sentence ended. A 2000 ms fixation cross appeared between trials. To help keep participants alert during this task, the yes/no questions about the pictures were randomly interspersed during the session. After 10% of the trials, a question mark appeared for 2000 ms instead of the fixation cross, which signaled that a question about the preceding picture would be presented. The presentation of the question was both visual and auditory, and it was followed by a screen prompting the participant to press 1 for "yes" or 2 for "no." A single set of yes/no questions was repeated with the same corresponding items in each session. Each training session was immediately followed by the sentence comprehension test described above. No feedback regarding the participants' accuracy was provided until the study was completed. Testing and training stimuli were presented on PC computers using SuperLab presentation software.

Data analysis—Performance accuracy during baseline and the training phase of the study was plotted as a line graph for each participant. Visual inspection of these data enabled identification of overall trends. For each participant, the mean accuracy across the baseline tests was subtracted from the mean accuracy in the final post-training test to provide a change score. For each participant, a treatment effect size was calculated by dividing this change score by the standard deviation of the baseline test scores (Beeson & Robey, 2006).

Results

Individual mean accuracy for the yes/no questions across the five training sessions was high (81.3%-96%, M=90.8%), indicating that participants were alert during training. Visual inspection of the passive sentence comprehension test data revealed two different trends among the five participants (see Figure 2). P1, P2, and P3 scored near chance (50%) throughout the baseline and training phases, whereas P4 and P5 showed declining accuracy during the training phase.

Table 3 displays change scores and effect sizes for the five participants. Two participants (P2 and P3) increased in overall passive sentence comprehension accuracy between baseline and the final post-test, and three participants (P1, P4, and P5) decreased. However, the effect sizes did not surpass the value of 6.0 that has been suggested as a benchmark for a small effect size for syntactic production treatment in single-subject research (see Beeson & Robey, 2006), with the exception of passive sentences with untrained verbs for P3 (effect size = 6.36).

The one participant in this experiment who showed no evidence of implicit sequence learning in Experiment 1 (P3) scored near chance throughout the baseline and training phases. The participant in this experiment who showed the largest implicit sequence learning effect in Experiment 1 (P1) also scored near chance throughout the baseline and training phases.

Discussion

The results of this experiment indicated that none of the five participants showed significant changes in comprehension of passive sentences following five sessions of the implicit treatment protocol, with the exception of a small effect size observed for passive sentences with untrained verbs for P3. With regard to overall passive sentence comprehension accuracy, three of the participants scored near chance performance throughout the training sessions, including P3, who showed no indication of implicit sequence learning in Experiment 1. The other two participants appear to have adopted a disadvantageous strategy during the training phase and consistently chose incorrect responses in the final post-training test.

A variety of factors may have impeded progress in this experiment. The passive sentence stimuli may have been particularly difficult to process due to their length (i.e., full passive sentences with an adjunct clause), and because the training task was not self-paced, the rate of stimulus presentation may have been too quick for some participants to fully process each sentence. Additionally, the yes/no questions included in the training sessions to keep participants alert may have encouraged them to attend to the pictures more than to the auditory sentences because the questions could be answered based solely on information from the visual stimuli.

Experiment 2b. Revised implicit sentence comprehension treatment

Introduction

In Experiment 2b we modified the experimental treatment protocol used in Experiment 2a in an attempt to improve learning. The same exposure-based training approach was used, but the sentence stimuli were shortened and increased time was provided during training and testing in an attempt to decrease processing difficulty. The yes/no questions used in Experiment 2a were eliminated to avoid the need to perform concurrent tasks. Additionally, Experiment 2b included an increased number of test sessions to track changes between training sessions and 24 hours after the last training session.

Methods

Participants—The remaining four individuals with aphasia who completed the SRTT in Experiment 1 (P6-P9) served as participants for this experiment. Participant descriptions and language testing data for these individuals are summarized in Tables 1 and 2. The participants demonstrated mild to moderate impairments in comprehension on the WAB Auditory Verbal Comprehension subtest, ranging in score from 5.3 to 8.5 out of 10 (M=7.2). Two of the four participants showed greater difficulty comprehending noncanonical compared to canonical sentence structures on the NAVS Sentence Comprehension Test, and all showed impairments in comprehending passive sentences on this test (M=40% correct) as well as during baseline testing.

Design—Experiment 2b was designed to address issues in Experiment 2a that may have impacted participants' learning. The passive sentence stimuli were shortened so that participants would not need to process an adjunct in addition to the by phrase required in full passive structures. Participants were not asked to perform any active task that might distract from the sentences during training, but instead merely listened to the sentences and viewed the pictures at their own pace to ensure that they had sufficient time to process each sentence. As a result of eliminating the yes/no questions that were included in Experiment 2a, the evidence of participants' engagement with the training task in Experiment 2b was simply a button press to advance to the next trial after each sentence was presented. In addition to converting the training task to a self-paced format, the testing procedures were changed so that there was no limit on response times, providing increased processing time during testing as well as training. Furthermore, only 10 different verbs were included in the training stimuli instead of 50 verbs so that participants would receive many repeated exposures to a limited set of verbs.

Experiment 2b was also designed to provide a more comprehensive assessment of participants' progress. In addition to baseline testing, participants were tested immediately before and after each training session, allowing for the examination of between-session changes in performance, and on the day after the last training session. Baseline testing and the final post-test included active and object cleft sentence structures in addition to passives. It was predicted that any improvement in passive sentence comprehension may generalize to improvement in simple active sentence comprehension for participants who were not already at ceiling for actives, whereas object cleft structures were included for control purposes. No improvement was expected for object clefts because the underlying syntactic structure of object clefts differs from that of passives, and generalization is unlikely to occur across complex sentences that are linguistically dissimilar (Thompson, Ballard, & Shapiro, 1998; Thompson, Shapiro, Kiran, & Sobecks, 2003).

This revised experiment again used a single-subject multiple baseline design across participants. Baseline sentence comprehension testing was administered 2-4 times prior to the start of training. Training consisted of five sessions. P6, P8, and P9 completed the five sessions on five consecutive days, whereas P7 had a two-day break between the third and the fourth sessions due to the participant's scheduling constraints. Each training session was immediately preceded and followed by 10 sentence comprehension trials that alternated between using passive sentences identical to the baseline test stimuli and passive sentences with the participant roles reversed. Additionally, participants returned on the day following their last training session to complete the full test that was administered during baseline testing.

Stimuli and procedures

Testing: The sentence comprehension test included 20 semantically reversible passive sentences with a by phrase, each with a different verb. The verbs used in 10 of the passive test sentences were also used in the training sentences, whereas the other 10 verbs were untrained. The 10 trained verbs were also used in 10 active sentences and in 10 object clefts to assess comprehension of these sentence structures (see Appendix C). The test sentences were recorded by a male native English speaker at a rate of approximately 3.5 words per second. As in Experiment 2a, for each sentence there was a line drawing depicting the correct meaning of the sentence and a second line drawing depicting the meaning of the sentence when the roles of the participants were reversed.

The sentence comprehension test used a computerized sentence-picture matching task similar to the one used in Experiment 2a. Prior to the first administration of the test, participants were familiarized with the picture stimuli. For each pair of pictures, the examiner named the verb and asked the participant to identify the people or animals in the pictures, e.g., "In this picture, the action is *poke*. Point to the boy in each picture… Now point to the girl in each picture". In the test, participants were asked to listen to each sentence and then press a key indicating whether the picture presented on the left or the right side of the monitor matched the sentence. Each trial began with a 2000 ms fixation cross. The two pictures were then displayed side-by-side for 2000 ms before auditory presentation of the sentence began. The pictures remained on the monitor until the participant responded. The different sentence types (i.e., active, passive, object cleft) were presented in separate blocks, with the order of the blocks randomized.

Training: For the training stimuli, each of the 10 trained verbs was used in four different sentence contexts, three semantically reversible and one irreversible, for a total of 40 passive sentences with a by phrase (see Appendix D). The training sentences were recorded by a female native English speaker at a rate of approximately 3.5 words per second. Photographs depicting each of the 40 sentences were selected from free online sources.

In each computerized self-paced training session, the set of 40 passive sentences and their corresponding pictures were presented in a random order four times, for a total of 160 trials lasting approximately 25 minutes. Participants were instructed to listen to the sentences and pay attention to how the sentences described what was happening in the pictures. In each trial, the picture appeared for 1000 ms before the auditory presentation of the sentence began, and it remained until the participant pressed the space bar to move on to the next trial. A 1000 ms fixation cross appeared between trials. Each training session was preceded and followed by 10 trials of the sentence-picture matching test using the trained verbs in passive sentences. These short tests during the training phase alternated between using passive sentences identical to the baseline test stimuli and passive sentences with the participant roles reversed. For example, if *The man was hugged by the girl* was presented in the test preceding a training session, then *The girl was hugged by the man* was presented in the test following that training session. No feedback regarding the participants' accuracy was provided until the study was completed. Testing and training stimuli were presented on PC computers using SuperLab presentation software.

Data analysis—The data analyses followed the same procedures as in Experiment 2a. Notably, the final post-training data that were entered into effect size calculations in this experiment were collected on the day after the last training session, whereas the final test in Experiment 2a occurred immediately after the last training session. For a more direct comparison with the results of Experiment 2a, in Table 4 we also provide effect sizes based on the data collected immediately after the last training session of Experiment 2b.

Results

Visual inspection of the data showed no clear changes in passive sentence comprehension (see Figure 3). Although P6 and P7 showed slight upward trends over the training phase, their accuracy for passive sentences with trained verbs in the final post-test was not far above chance performance, and their accuracy for passive sentences with untrained verbs in the final post-test was not above chance. P8 and P9 scored near chance throughout the baseline and training phases.

Table 4 displays change scores and effect sizes for sentence comprehension for the four participants. Two participants (P6 and P8) increased in overall passive sentence comprehension scores between baseline and the final post-test, and two participants (P7 and P9) decreased. As in Experiment 2a, the effect sizes did not surpass the value of 6.0 that has been suggested as a benchmark for a small effect size for syntactic production treatment in single-subject research (see Beeson & Robey, 2006). Similarly, effect sizes for active and object cleft sentence structures did not surpass this benchmark.

The one participant in this experiment who showed no indication of implicit sequence learning in Experiment 1 (P7) showed an upward trend during the training phase but scored near chance on passive sentences in the post-test. The participant in this experiment who showed the largest indication of implicit sequence learning in Experiment 1 (P9) showed variable performance during the training phase and scored near chance on passive sentences in the post-test.

Discussion

The results of Experiment 2b showed no clear changes in passive sentence comprehension using the revised training protocol, which included shorter sentence stimuli and provided more processing time compared to Experiment 2a by converting the training task to a self-paced format and eliminating response time limits during the tests. The participants in this experiment received a total of 800 exposures to passive sentences with matching pictures over the five training sessions, but none of the four participants showed significant improvement in passive sentence comprehension. It is important to note, however, that participants' performance during the baseline phase was somewhat variable, and this variability may have reduced the emergence of larger effect sizes. The performance of the participant who showed no indication of implicit sequence learning in Experiment 1 (P7) was largely similar to that of the other three participants.

General discussion

This study examined implicit visuomotor sequence learning in the SRTT, a well-established implicit learning paradigm that does not require linguistic processing or production, in a group of individuals with aphasia, and whether individuals with aphasia who show implicit learning ability in the SRTT respond to an implicit language treatment focused on passive sentence comprehension. In Experiment 1, the group of individuals with aphasia showed a significant increase in reaction time between the sequenced and random blocks of the SRTT, indicating implicit learning of the sequence. These results were similar to those of the neurologically intact comparison group and were fairly consistent among individual participants, with 7/9 participants with aphasia showing a reaction time increase. This evidence of implicit sequence learning in individuals with agrammatic aphasia has important implications for the mechanisms underlying sequence learning and language. The results conflict with the idea that agrammatic aphasia is associated with damage to domain-general mechanisms that subserve both sequence learning and syntactic processing (Christiansen et al., 2010). Although previous studies have shown impairments in implicit sequence learning co-occurring with syntactic impairments after brain injury (Christiansen et al., 2010; Zimmerer et al., 2014), the present results suggest otherwise and support previous studies showing implicit sequence learning ability in people with agrammatic aphasia (Goschke et al., 2001; Schuchard & Thompson, 2014; Schuchard & Thompson, in preparation). Future studies should be designed to examine factors such as lesion site that may contribute to the variability in implicit learning abilities in this population, which will further the understanding of the neural mechanisms underlying learning and language.

Although the participants with aphasia in this study showed implicit learning in the SRTT, they showed little benefit from implicit sentence comprehension training consisting of exposure to grammatically correct passive sentences. Previous exposure-based, errorless learning methods have been shown to improve naming in aphasia (Conroy et al., 2009; Fillingham et al., 2005a; 2005b; 2006; McKissock & Ward, 2007), but there are notable differences between errorless learning interventions for anomia and the treatment in the present study that could account for the ineffectiveness of implicit training in improving sentence comprehension. Errorless learning interventions for anomia require a response from the participant in each trial (i.e., repetition of a word), whereas the implicit sentence comprehension training did not require behavioral responses. Furthermore, naming (production) treatment involves lexical retrieval, whereas treatment for sentence comprehension requires both lexical (access) and syntactic processing. Improving comprehension of syntactically complex sentence structures may require active training and/or explicit instructions, as is provided in Treatment of Underlying Forms (TUF), which focuses on knowledge of verb argument structure as well as syntactic operations (Thompson & Shapiro, 2005).

It is important to note, however, that the results of the implicit treatment protocols are preliminary, and their interpretation is limited by methodological issues. The experiments reported here included relatively small numbers of participants and involved training only one sentence structure (i.e., passive sentences) over five sessions. Furthermore, several participants demonstrated variability on the sentence-picture matching test across the 2-4 baseline probes. Variability during the baseline phase and small numbers of baseline probes complicate the interpretation of changes during the training phase and contribute to lower effect sizes, thereby potentially underestimating treatment effects. Indeed, visual inspection of the data suggests generally positive effects for some participants, particularly in Experiment 2b. To better evaluate the efficacy of implicit language treatment, effects of implicit training methods should be directly compared to those of explicit training methods. For example, Middleton and colleagues (2014) tested naming training based on errorless learning and naming training based on lexical retrieval attempts and found that retrieval practice produced greater retention of gains in people with aphasia. Although this finding and the present results suggest that relying solely on exposure-based, errorless learning may not be the most effective approach to language rehabilitation, further research may reveal benefits of implicit training approaches, either in isolation or in combination with more explicit training methods.

Limitations of the present study also precluded a thorough investigation of the relationship between implicit learning abilities and implicit sentence comprehension treatment. Because the implicit treatment was not effective, any potential association between improvement in linguistic skills and performance in the implicit learning task could not be examined. Additionally, the study included a single, non-linguistic task to assess implicit learning abilities. The visuomotor SRTT was selected because performance in the task is not confounded with language processing or production. However, learning tasks in the verbal domain may be better predictors of the ability to learn in linguistic interventions. Furthermore, other implicit learning paradigms, such as artificial grammar learning, are arguably more relevant to the regularities that occur in natural language because they can include hierarchical phrase structure rules (e.g., Saffran, 2001; 2002) as opposed to the relatively simple sequence learning in the SRTT. Ideally, assessments of implicit learning abilities should include multiple tasks to test learning for different types of structures in different domains.

Although implicit learning ability did not translate to success in the implicit sentence treatment provided in this study, the relationship between basic learning abilities and treatment outcomes in aphasia remains an important and relatively unexplored area of research. Learning outcomes among individuals with aphasia range from normal to impaired in non-linguistic implicit sequence learning (Zimmerer et al., 2014) and non-linguistic category learning tasks (Vallila-Rohter & Kiran, 2013a; 2013b), suggesting that some individuals have learning deficits that cannot be attributed to their linguistic deficits. A better understanding of how learning impairments such as these impact the efficacy of different training approaches has potential to inform effective language treatment and help elucidate the mechanisms underlying learning and language. For example, in a study of novel word learning, one woman with aphasia showed superior learning when new words were presented orthographically as opposed to auditorily, demonstrating that learning abilities can be modality-specific, and this advantage of written input translated to a useful strategy in language treatment for her (Tuomiranta et al., 2014). Further language treatment research that includes relevant assessments of learning abilities will provide valuable insights into the underlying processes and individual characteristics that promote language recovery.

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Appendix A: Experiment 2a Test Stimuli

Sentences including trained verbs:

The woman was called by the man at the house.

The girl was cleaned by the woman in the bathroom.

The woman was covered by the man on the chair.

The boy was examined by the girl in the classroom.

The dog was followed by the cat in the woods.

The man was hugged by the girl in the family room.

The woman was observed by the man on the street.

The boy was poked by the girl in the library.

The man was shaved by the boy in the barbershop.

The girl was tickled by the boy in the playroom.

Sentences including untrained verbs:

The boy was buried by the woman at the beach.

The boy was captured by the girl under the tree.

The man was carried by the woman at the hotel.

The woman was combed by the man at the salon.

The girl was greeted by the man at the door.

The girl was kicked by the boy in the park.

The man was photographed by the woman at the concert.

The cat was scratched by the dog in the yard.

The boy was tackled by the girl on the grass.

The man was touched by the woman at the party.

Appendix B: Experiment 2a Training Stimuli

The receptionist was called by the customer at the desk.

The counter was cleaned by the maid in the kitchen.

The doll was covered by the child in the hallway.

The patient was examined by the doctor at the hospital.

The bird was followed by the boy in the park.

The boy was hugged by the child near the house.

The ocean was observed by the tourist on the porch.

The fire was poked by the woman in the cabin.

The customer was shaved by the woman at the salon.

The child was tickled by the sister on the bed.

The bird was watched by the hiker near the tree.

The cheerleader was supported by the boy on the field.

The woman was soaked by the bus on the street.

The daughter was soothed by the father on the couch.

The drink was poured by the man in the office.

The medicine was injected by the woman at the hospital.

The car was polished by the man in the garage.

The baby was bathed by the parent in the bathroom.

The tree was decorated by the children in the school.

The wound was healed by the nurse in the hospital.

The class was entertained by the performer at the school.

The food was offered by the man near the kitchen.

The newspaper was ripped by the woman at the table.

The woman was rubbed by the masseuse at the salon.

The table was wiped by the maid in the office.

The bridge was crossed by the hikers in the mountains.

The grain was crushed by the worker at the farm.

The pepper was sliced by the woman in the kitchen.

The essay was edited by the student on the computer.

The tank was filled by the teenager at the station.

The batter was stirred by the baker in the café.

The pulse was measured by the doctor in the clinic.

The journal was opened by the writer at the desk.

The kayak was paddled by the man in the river.

The plate was passed by the woman on the deck.

The apple was peeled by the chef in the restaurant.

The businessman was phoned by the friend in the office.

The guitar was tuned by the musician in the apartment.

The instrument was strummed by the musician on the stage.

The game was played by the team on the field.

The marshmallow was roasted by the camper over the fire.

The tree was pruned by the volunteer in the woods.

The swimmer was rescued by the crew in the boat.

The cabbage was chewed by the rabbit on the floor.

The flower was smelled by the girl in the house.

The boat was steered by the crew on the lake.

The sunset was viewed by the boy on the beach.

The child was splashed by the brother in the pool.

The food was prepared by the man in the restaurant.

The group was sprayed by the fountain in the park.

Appendix C: Experiment 2b Test Stimuli

Passive sentences including trained verbs:	**Active sentences including trained verbs:**
The man was called by the woman.	The man was calling the woman.
The girl was cleaned by the woman.	The girl was cleaning the woman.
The woman was covered by the man.	The woman was covering the man.
The boy was examined by the girl.	The boy was examining the girl.
The cat was followed by the dog.	The cat was following the dog.
The man was hugged by the girl.	The girl was hugging the man.
The man was observed by the woman.	The woman was observing the man.
The boy was poked by the girl.	The girl was poking the boy.
The man was shaved by the boy.	The boy was shaving the man.
The girl was tickled by the boy.	The boy was tickling the girl.
Passive sentences including untrained verbs:	**Object clefts including trained verbs:**
The cat was scratched by the dog.	It was the man who the woman called.
The boy was buried by the woman.	It was the woman who the girl cleaned.
The boy was captured by the girl.	It was the woman who the man covered.
The woman was combed by the man.	It was the girl who the boy examined.
The man was photographed by the woman.	It was the cat who the dog followed.
The girl was greeted by the man.	It was the man who the girl hugged.

The girl was tackled by the boy.	It was the woman who the man observed.
The man was carried by the woman.	It was the boy who the girl poked.
The girl was kicked by the boy.	It was the boy who the man shaved.
The man was touched by the woman.	It was the girl who the boy tickled.

Appendix D: Experiment 2b Training Stimuli

The woman was called by the man.

The man was called by the woman.

The wife was called by the husband.

The taxi was called by the woman.

The man was cleaned by the woman.

The woman was cleaned by the man.

The child was cleaned by the mother.

The kitchen was cleaned by the woman.

The parent was covered by the child.

The child was covered by the parent.

The child was covered by the mother.

The doll was covered by the child.

The man was examined by the woman.

The woman was examined by the man.

The patient was examined by the doctor.

The flower was examined by the boy.

The dog was followed by the cat.

The cat was followed by the dog.

The boy was followed by the dog.

The car was followed by the dog.

The girl was hugged by the man.

The man was hugged by the girl.

The brother was hugged by the sister.

The doll was hugged by the girl.

The man was observed by the woman.

The woman was observed by the man.

The dog was observed by the boy.

The sunrise was observed by the boy.

The woman was poked by the man.

The man was poked by the woman.

The husband was poked by the wife.

The fire was poked by the woman.

The man was shaved by the woman.

The woman was shaved by the man.

The brother was shaved by the sister.

The beard was shaved by the man.

The boy was tickled by the girl.

The girl was tickled by the boy.

The child was tickled by the mother.

The baby was tickled by the father.

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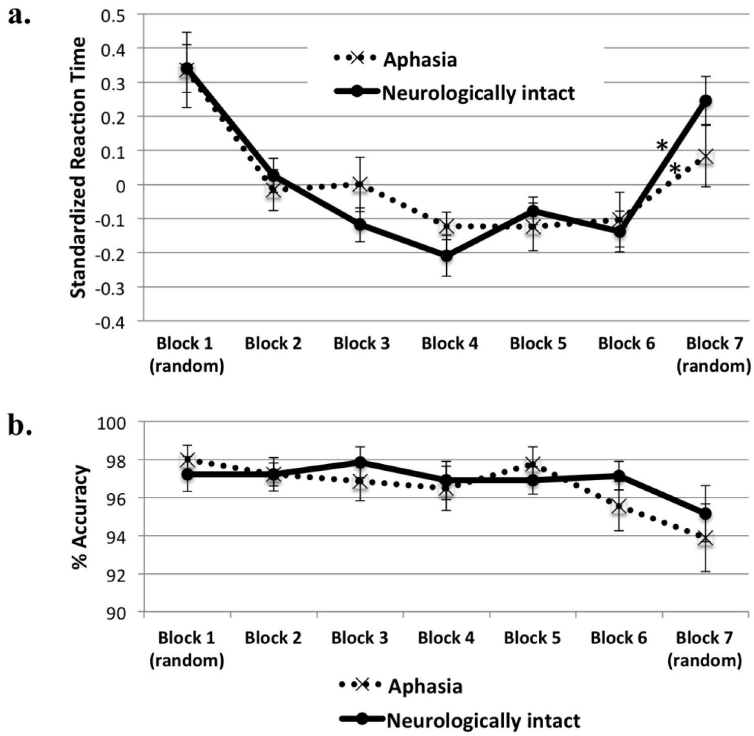

Figure 1.

Average standardized reaction time (1a) and percent accuracy (1b) across the seven blocks of the SRTT for the group of individuals with aphasia and the group of neurologically intact adults. Bars indicate one standard error above and below the mean. Implicit sequence learning in this paradigm is indicated by significantly higher reaction time in the final random block (Block 7) compared to the preceding sequenced block (Block 6).

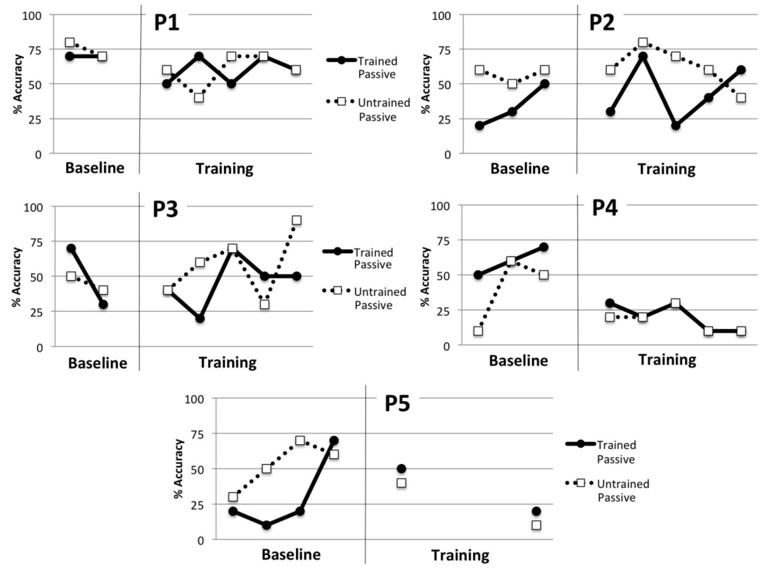

Figure 2.
Percent correct performance on the sentence comprehension test for passive sentences with trained verbs (“Trained Passive”) and passive sentences with untrained verbs (“Untrained Passive”) for each participant in Experiment 2a. Chance performance is 50% correct. Missing data for training sessions 2-4 for P5 are due to technical errors on those days.

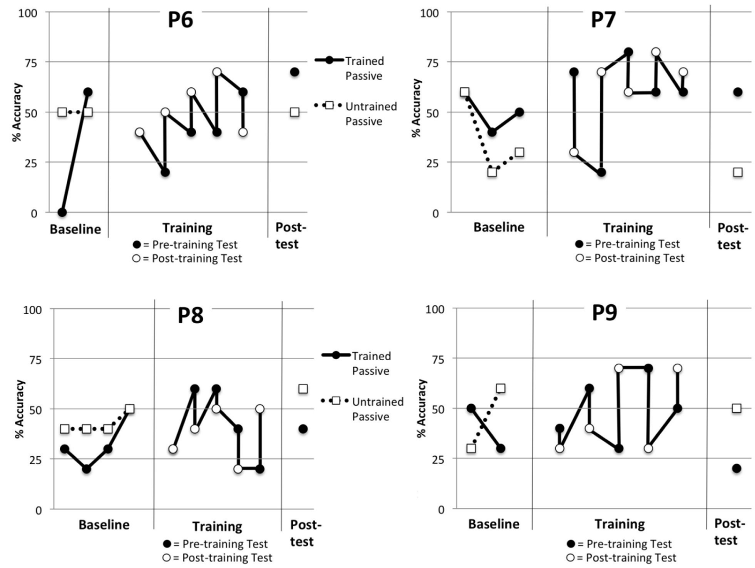

Figure 3.
Percent correct performance on the sentence comprehension test for passive sentences with trained verbs ("Trained Passive") and passive sentences with untrained verbs ("Untrained Passive") for each participant in Experiment 2b. Chance performance is 50% correct. Tests administered immediately prior to and after each session of the training phase included only trained passives. Vertical lines show changes in accuracy within days, and horizontal or diagonal lines show changes in accuracy across days.

Table 1

Demographic information for participants with aphasia

Participant	Age	Gender	Years post-onset	Years of education
P1	51	M	6	16
P2	53	M	3	18
P3	35	F	5	18
P4	51	F	6	13
P5	53	F	8	12
P6	44	F	3	20
P7	65	M	23	19
P8	46	M	2	16
P9	44	F	5	16
Mean	**49.1**		**6.8**	**16.4**

Table 2

Selected language testing scores for participants with aphasia

Assessment	P1	P2	P3	P4	P5	P6	P7	P8	P9	Mean
Western Aphasia Battery										
Aphasia Quotient	69.7	77.2	82.5	74.8	53	n/a	71.7	59	51.5	**67.4**
Fluency	4	4	6	6	2	2	4	4	4	**4.0**
Content	9	9	10	8	5	2	9	8	5	**7.2**
Auditory Comprehension	9.3	8.3	7.6	7	8	5.3	8.5	8.3	6.6	**7.7**
Repetition	6.6	7.2	9	8.4	6.4	n/a	5.1	3.2	3.4	**6.2**
Naming and Word Finding	6	8.1	8.7	8	5.1	n/a	9.3	6	6.8	**7.3**
Northwestern Assessment of Verbs and Sentences										
Sentence Production										
Canonical sentences	80	46.7	80	73	73.3	n/a	73.3	n/a	6.7	**61.9**
Noncanonical sentences	13.3	0	46.7	46.7	40	n/a	0	n/a	0	**21.0**
Sentence Comprehension										
Canonical sentences	66.7	80	66.7	87	93.3	33.3	93.3	66.7	46.7	**70.4**
Noncanonical sentences	66.7	26.7	73.3	53.3	33.3	53.3	73.3	40	53.3	**52.6**
Cinderella speech sample										
% grammatical sentences	0.0	0.0	93.3	64.7	0.0	n/a	0.0	34.5	n/a	**27.5**
Words per minute	42.3	32.2	54.4	42.8	36.4	n/a	70.9	68.7	n/a	**49.7**

Note. The highest possible WAB Aphasia Quotient (AQ) is 100 (with neurologically intact adults scoring an average of 98.4 (Kertesz, 2007)); the highest possible score for each WAB subtest is 10. NAVS scores represent percentage correct. Tests indicated as n/a were discontinued or not administered due to the severity of the participant's production impairments.

Table 3

Passive sentence comprehension accuracy in Experiment 2a

Participant	Baseline	Final post-test	Change score	Effect size
P1				
Trained verbs	70	60	−10	−2.83*
Untrained verbs	75	60	−15	−2.12
All passives	72.5	60	−12.5	−3.54
P2				
Trained verbs	33.3	60	26.7	1.75
Untrained verbs	56.7	40	−16.7	−2.89
All passives	45	50	5	0.58
P3				
Trained verbs	50	50	0	0
Untrained verbs	45	90	45	6.36
All passives	47.5	70	22.5	1.27
P4				
Trained verbs	60	10	−50	−5
Untrained verbs	40	10	−30	−1.13
All passives	50	10	−40	−2.31
P5				
Trained verbs	30	20	−10	−0.37
Untrained verbs	52.5	10	−42.5	−2.49
All passives	41.3	15	−26.3	−1.46

Note. Scores represent percent accuracy for passive sentences with trained verbs, passive sentences with untrained verbs, and all passive sentences across the baseline sessions and in the final post-testing session. These scores were used to calculate change scores and effect sizes for each participant.

*Because an effect size cannot be calculated when there is no variance between baseline sessions, here we substituted the standard deviation for all passives at baseline for P1 in the calculation of the effect size.

Table 4

Sentence comprehension accuracy in Experiment 2b

Participant	Baseline	Post-training session 5	Final post-test	Change score	Effect size
P6					
Trained verbs	30.0	40.0	70.0	40.0 (10.0)	0.94 (0.24)
Untrained verbs	50.0		50.0	0.0	0.00
All passives	40.0		60.0	20.0	0.94
Actives	65.0		50.0	−15.0	−2.12
Object clefts	50.0		60.0	10.0	0.71
P7					
Trained verbs	50.0	70.0	60.0	10.0 (20.0)	1.00 (2.00)
Untrained verbs	36.7		20.0	−16.7	−0.80
All passives	43.3		40.0	−3.3	−0.22
Actives	96.7		100.0	3.3	0.58
Object clefts	63.3		30.0	−33.3	−2.18
P8					
Trained verbs	32.5	50.0	40.0	7.5 (17.5)	0.60 (1.39)
Untrained verbs	42.5		60.0	17.5	3.50
All passives	37.5		50.0	12.5	1.44
Actives	82.5		80.0	−2.5	−0.50
Object clefts	35.0		30.0	−5.0	−0.39
P9					
Trained verbs	40.0	70.0	20.0	−20.0 (30.0)	−1.41 (2.12)
Untrained verbs	45.0		50.0	5.0	0.24
All passives	42.5		35.0	−7.5	−2.12
Actives	45.0		40.0	−5.0	−0.71
Object clefts	40.0		60.0	20.0	1.41

Note. Scores represent percent accuracy for passive sentences with trained verbs, passive sentences with untrained verbs, all passive sentences, actives, and object clefts across the baseline sessions and in the final post-testing session. These scores were used to calculate change scores and effect sizes for each participant. Passive sentences with trained verbs were also tested immediately following the last training session, and change scores and effect sizes using scores on this test are reported in parentheses in the appropriate rows.