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Visual statistical learning is not reliably modulated by selective attention to isolated events

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Abstract

Recent studies of visual statistical learning (VSL) indicate that the visual system can automatically extract temporal and spatial relationships between objects. We report several attempts to replicate and extend earlier work (Turk-Browne et al., 2005) in which observers performed a cover task on one of two interleaved stimulus sets, resulting in learning of temporal relationships that occur in the attended stream, but not those present in the unattended stream. Across four experiments, we exposed observers to a similar or identical familiarization protocol, directing attention to one of two interleaved stimulus sets; afterward, we assessed VSL efficacy for both sets using either implicit response-time measures or explicit familiarity judgments. In line with prior work, we observe learning for the attended stimulus set. However, unlike previous reports, we also observe learning for the unattended stimulus set. When instructed to selectively attend to only one of the stimulus sets and ignore the other set, observers could extract temporal regularities for both sets. Our efforts to experimentally decrease this effect by changing the cover task (Experiment 1) or the complexity of the statistical regularities (Experiment 3) were unsuccessful. A fourth experiment using a different assessment of learning likewise failed to show an attentional effect. Simulations drawing random samples our first three experiments (n=64) confirm that the distribution of attentional effects in our sample closely approximates the null. We offer several potential explanations for our failure to replicate earlier findings, and discuss how our results suggest limiting conditions on the relevance of attention to VSL.

Our sensory environment is composed of both random and regular variation. Humans are often capable of extracting the regular variation, unconsciously and unintentionally, from the random variability in which it is embedded, and using that extracted knowledge to guide future actions. Such learning phenomena can be implicit and incidental: Observers can learn, not only without trying, but also without becoming aware that they had learned anything at all.

The domain-general mechanisms of implicit learning have been studied extensively, beginning with studies of artificial grammar learning in the late 1960s (Reber, 1967), and continuing with research in subfields diverse as motor learning and language acquisition. One variant of implicit learning is known as *statistical learning* (see Perruchet & Pacton,

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2006, for a discussion of the relationship between these lines of research). This term refers to the extraction of regularities from continuous environments, where the only cues for segmentation are the statistics of how frequently specific stimuli co-occur (Turk-Browne, Scholl, Johnson, & Chun, 2010). This phenomenon was first reported using auditory stimuli, and has greatly elucidated the mechanisms through which young children learn to segment words from an uninterrupted stream of spoken syllables (Saffran, Aslin, & Newport, 1996). However, statistical learning is not limited to the linguistic domain; it is also observed for nonlinguistic auditory stimuli like music tones (Saffran, Johnson, Aslin, & Newport, 1999; Creel, Newport, & Aslin, 2004), and for visual regularities consisting of repeated spatial and temporal configurations of shapes, locations, motions, and actions. The focus of our studies is this latter form of statistical learning, called visual statistical learning (VSL).

Several studies have found evidence of this learning phenomenon in adults as well as infants (e.g., Kirkham, Slemmer, & Johnson, 2002; Bulf, Johnson, & Valenza, 2011). VSL appears to be largely automatic, occurring unintentionally even for temporal sequences of nonsense items that appear to be randomly ordered (Fiser & Aslin, 2002a). In addition to inter-item transitional probabilities, VSL can operate over spatial regularities (Chun & Jiang, 1998; Jiang & Chun, 2001; Fiser & Aslin, 2001, 2002b; Baker, Olson, & Behrmann, 2004; Zhao, Ngo, McKendrick, & Turk-Browne, 2011); over bound shape-color object pairs (Turk-Browne, Isola, Scholl, & Treat, 2008); at various spatial scales (Fiser & Aslin, 2005); during an orthogonal task (Turk-Browne, Jungé, & Scholl, 2005); and despite interleaved noise (Jungé, Turk-Browne, & Scholl, 2005).

Although implicit learning is often characterized as “incidental” or “automatic,” it is often—but not always—modulated by attention. In artificial grammar learning tasks, attention to structure at one level (e.g., local versus global levels in Navon figures) supports learning only at that level (Tanaka, Kiyokawa, Yamada, Dienes, & Shigemasu, 2008), suggesting that attention is necessary for learning. Pacton & Perruchet (2008) demonstrated a similar effect for adjacent versus nonadjacent structures in sequences of numbers. Many studies have documented the robustness of the serial response time (SRT) task amidst attentionally demanding secondary tasks (e.g., Cohen, Ivry, & Keele, 1990; Jiménez & Méndez, 1999; Hsiao & Reber, 2001), but other studies have reported contradictory results (for a review, see Shanks, Rowland, & Ranger, 2005). However, Jiménez & Méndez (1999) highlight a useful distinction between divided and selective attention. In their studies, subjects were exposed to a sequence of shapes, each of which was more likely than not to appear in a certain location on the screen. Learning of the shape-location contingencies was unaffected when subjects’ attention was divided by counting some of the shapes, but it was eliminated when subjects were directed not to attend to the shapes, suggesting that selective attention to the informative dimensions of the stimulus is necessary for learning. Curran & Keele (1993) suggest a specific role for attention in learning an event’s position within a sequence, operating alongside a nonattentional learning mechanism that only registers associative information. Thus, attentional effects on statistical learning are well attested, but highly sensitive to the particulars of the task and the attentional manipulation.

In the statistical learning paradigms that inspired those employed in the present series of experiments, incidental (and thus perhaps inattentional) learning has been demonstrated in the auditory domain when subjects are presented with a distracting cover task, although learning without the cover task is much faster (Saffran, Newport, Aslin, Tunick, & Barrueco, 1997). Toro, Sinnett, & Soto-Faraco (2005) and Turk-Browne et al. (2005) also document effects of attention in various statistical learning paradigms; however, Campbell, Zimerman, Healy, Lee, & Hasher (2012) replicate those effects in younger but not older adults, suggesting that selective attention is not always capable of extinguishing learning of unattended stimuli.

The assessment of implicit learning might influence whether or not attentional effects are observed. The majority of the work summarized above relies upon explicit judgments of familiarity to index learning. In contrast, Turk-Browne et al. (2005), Experiment 3, and Campbell et al. (2012) use an implicit measure for learning, which has the potential to be more sensitive than overt familiarity judgments. We will summarize the implicit measure and corresponding paradigm at some length, as their details will be relevant to our interpretation of the results. In the learning phase, participants were exposed to two shape sequences, one from a set of green shapes and one from a set of red shapes. Unbeknownst to the participants, shapes of a given color were organized into regular triplets, such that the first shape in a triplet was always followed by the second, and the second always followed by the third. The red triplets were then organized into a red stream, which contained many repetitions of each red triplet; the same was done with the green triplets. In each stream, the first or third shape of a triplet was occasionally repeated. The streams were then randomly interleaved to form a final stream, and subjects were exposed to the final stream one shape at a time. To manipulate attention, subjects performed a modified one-back task: they were instructed to detect shape repetitions in either the red or the green shapes, but not the other color (see Figure 1a). Thus, subjects were required to maintain the identity of the most recently presented “attended” shape over a variable number of presentations of “unattended” shapes.

In most studies of statistical learning, subjects’ learning is assessed by familiarity judgments on stimulus sequences with strong versus weak inter-item transitional probabilities. In the visual paradigm used by Turk-Browne et al. (2005), learning was predominantly evaluated by these explicit familiarity judgments. After the familiarization phase, observers perform a surprise two-interval force choice familiarity task, which pits true triplets against foil sequences (see Figure 1b). Although all shapes are presented in black to avoid continued effects of attentional set, observers were expected to exhibit relatively higher accuracy for shapes derived from the originally attended color stream. However, in their Experiment 3, learning was assessed as subjects responded as quickly as possible to the appearance of a target shape in a speeded, sequential stream of other shapes. The signature of learning is a progressive drop in reaction times for target shapes that regularly appeared in the second and third triplet positions. They reasoned that shapes in the first position are not predicted by the preceding shape, whereas those in the second and third positions are (and those in the third position are predicted by the preceding two); thus, shapes in subsequent serial positions should elicit faster reaction times if subjects had actually learned the structure of the stimuli. In healthy college students, Turk-Browne et al. (2005) and Campbell et al. (2012) found an attentional effect on this signature of learning; the progressive decrease in reaction times was found for stimuli in the attended but not the unattended stream.

This implicit signature of learning has the potential to be more sensitive than explicit forced-choice familiarity judgments, which might suggest that its reported absence for shapes in the unattended stream constitutes very strong evidence against learning without attention. However, during the familiarization phase, there is a critical confound in the one-back cover task: It necessitates comparison of each stimulus in the attended stream to each preceding one, whereas there is no parallel demand for relational processing in the unattended stream. This explicit relational processing might naturally invite learning about the temporal relationships between adjacent stimuli. Relational processing of the attended stimuli, rather than attention itself, might thus account for the reported statistical learning advantage for shape regularities from the attended stimulus set. Note that, in principle, observers could selectively attend to the stimuli in the attended stream without explicitly comparing adjacent elements. Such a manipulation would more purely assess the effect of attention on VSL.

The present article begins with just such a manipulation: In Experiment 1, we used the 24 shapes used by Turk-Browne et al. (2005), but added a 25th, which was presented in both streams in lieu of repeated shapes. Subjects were instructed to detect the appearance of the 25th shape in the attended stream, rather than repetitions. We reasoned that this procedure would manipulate attention—and perhaps even increase the need for selection, since lure shapes also appeared in the unattended stream—while removing the need for relational processing, providing a fairer test of the role of attention in VSL.

To foreshadow, observers exposed to this familiarization protocol showed learning in both attended and unattended streams. As we were surprised by these results, we attempted a direct replication of the original findings reported in Turk-Browne et al.'s (2005) Experiment 3, using their original cover task (Experiment 2). Again, VSL effects persisted for both attended and unattended stimulus sets. We then attempted to reveal learning differences between the stimulus sets by weakening the statistical structure of both streams (Experiment 3), and tested whether the effects depended on the test used to assess learning (Experiment 4). Simple simulations supported our overall results. Across several variations of the experiment and 88 total subjects, we found that, when attention to temporally segmented visual regularities is manipulated by stimulus color, subjects learn just as well from the unattended as the attended stream. Thus, the learning of temporal structure may be more robust and less subject to attentional constraints than previously thought.

We do not wish to claim that selective attention is irrelevant to VSL; that would require more support than a handful of experiments using variations on a single paradigm. However, our results suggest that simply directing subjects to attend to a subset of centrally presented stimuli may not reliably manipulate attention strongly enough to suppress VSL. We begin by detailing our first revision of the Turk-Browne et al. (2005) task, and then proceed to explain each sequential replication and modification to this experimental design.

General Methods and Procedure

Each study reported below had two distinct phases, which we will refer to as a *familiarization phase* and a *test phase*. In the familiarization phase, we exposed subjects to the statistical structure of the sequence while they performed a cover task; the attentional manipulation was introduced during this phase. In the test phase, we assessed subjects' learning of those sequences; in Experiments 1–3 we assessed learning implicitly, while subjects performed a target detection task. Importantly, in neither phase were subjects required to attend to the sequences of stimuli that are of interest to us. Thus, both learning and testing were implicit. (In Experiment 4, we switched to a more explicit test of learning.)

The critical manipulation occurred during the familiarization phase: In order to test for the effects of attention on learning, we directed subjects' attention to some stimuli (but not others) by cueing them to perform the cover task on one of two colored stimulus sets. The design (both familiarization and test) closely replicates that of Turk-Browne et al. (2005), Experiment 3. The methods described below apply to all experimental manipulations unless otherwise specified.

Apparatus and Stimuli

The stimulus streams comprised 24 novel shapes, as described in Turk-Browne et al. (2005). Each shape could appear in green or red (counterbalanced across subjects, during the familiarization phase) or in black (during the test phase). Each shape appeared in the center of the screen, subtending approximately 3.3 degrees of visual angle. All displays were presented on a 17-inch Dell monitor, and observers sat approximately 60 cm from the display. The displays were presented using PsychoPy software (Peirce, 2007).

Familiarization Sequences

Of the 24 novel shapes, 12 were randomly assigned to the green set, and the other 12 were assigned to the red set. Within each color set, the 12 shapes were further divided into four groups with three shapes per group, hereafter referred to as "triplets." Each triplet was repeated 24 times. The triplets were then intermixed to randomize the between-triplet sequence order, but their within-triplet order was always maintained. However, there were two constraints to the triplet sequences: triplets could not presented twice in a row, and two triplets could not alternate in an ABAB pattern. Additional shapes were then added to these sequences to allow for a cover task, and the subsequent sequence manipulation will be described separately for each experiment. Each color set ultimately consisted of 312 shapes. Across participants, we counterbalanced the presentation of either these stimulus sequences or their reverses, as well as the color of the attended stream (red or green).

Interleaving Sequences for Familiarization

After the red and green triplet sequences were assembled independently from one another, they were randomly interleaved into a single long shape stream at the time of stimulus presentation. Thus, the shape presented at any given time was equally likely to be the next shape from the red or the green sequence. The only other constraint in the interleaving was that a given color could be presented a maximum of six times in a row. The resulting interleaved sequence was 624 shapes in length.

Familiarization Phase

Participants sat in a dimly lit room, and the experimenter verbally described the first half of the experiment. Participants were instructed that they would see a series of red and green shapes presented one at a time. To bias attention to a subset of the shapes, participants were told to only attend to one of the shape sets and to ignore shapes of the other color. Additionally, they were instructed to perform a concurrent task on shapes from only the attended color set. This concurrent task varied across experiments.

Participants completed a practice session with 30 shapes. In this practice session and the familiarization phase that followed it, shape sequences appeared at a stimulus onset asynchrony (SOA) of 1,000 ms, with an interstimulus interval (ISI) of 200 ms. Thus, each shape appeared for 800 ms. Accuracy and RTs were recorded to confirm that participants completed the cover task. The familiarization phase lasted approximately ten minutes.

Implicit Test Phase

Immediately after the presentation of all 624 shapes, instructions for the test phase began. The same shape stimuli were presented in the test phase. To avoid the possibility of intrusive attentional set effects, these shapes now all appeared in black rather than their original colors. At the beginning of each trial, one of the shapes would appear in the center of the screen; participants were instructed that this shape would serve as the trial's target shape. After pressing a key to start the trial, there was a 1,000 ms delay, followed by a sequence of shapes that appeared in quick succession. Each shape was presented at an SOA of 400 ms, and 200 ms ISI. Thus, each shape appeared for 200 ms. The participants were instructed to detect the target shape in the ensuing test sequence via an immediate key press. Each test trial consisted of 24 shapes, consisting of two repetitions of each of the four triplets that were originally from the same color set as the target shape in the familiarization phase. Therefore, each test target appeared twice in the test sequence. Each of the 24 shapes from the familiarization phase served as a test target four times, resulting in 96 total test trials presented in a random order. Detection accuracies and RTs were recorded on every trial, and the task was approximately 17 minutes long.

The dependent measure was the observer's reaction time for detecting the target shape. Critically, this target shape could have originally been the first, second, or third shape in a triplet in the familiarization phase. We operationalized learning as speeded response times for shapes that had appeared second or third in their respective triplets: Subjects who had learned the structure of the input should have been able to use that information to predict what was coming next and thus detect it faster. If the attentional manipulation effectively gated VSL, then this pattern of results should only have occurred for shapes that were originally from the attended stream, not for those from the unattended stream. However, if the manipulation did not affect VSL, then observers should have been able to learn triplets from both of the shape streams equally well.

Data Analysis

Participants were removed from the analysis if their mean performance on the familiarization or test tasks (accuracy or response latency) was over 2.5 standard deviations away from the group's mean. Test trials were split into attended and unattended target groups, based on each shape's original assignment from the familiarization phase. They were then further split according to each test target's original position within its corresponding triplet in the familiarization phase. Matching the analysis for Experiment 3 in Turk-Browne et al. (2005), this yielded a 2 (color stream: attended vs. unattended) ´ 3 (intra-triplet position: first, second, or third) design, with 32 RTs for each of the six cells. Within each cell, response times were trimmed by removing responses that fell 3 standard deviations outside each participant's own mean.

Experiment 1: Shape detection cover task

This experiment tested attentional modulation of VSL under conditions in which the concurrent cover task did not require processing the relationships among adjacent attended stimuli—in contrast to the studies reported by Turk-Browne et al. (2005), in which the one-back cover task required comparing each attended stimulus to the preceding one. We viewed detection of a simple target (a specific shape) that appeared in both streams, rather than a relational target (a repetition), as a stronger test of the role of attention, as distinct from relational processing, in VSL.

Method

Our cover task was a simple shape detection task. This design largely replicated the structure of Turk-Browne et al. (2005), Experiment 3, except for a few important changes. Instead of a one-back task on the attended stream, the observer's task was to detect the appearance of one specific, sporadically inserted shape, which was prespecified for the observer at the beginning of the experiment. Attention was still manipulated by color set; although the extra shape was inserted in both color streams, observers were instructed to respond to it only when it appeared in their assigned color. This shape was not a member of any triplet, and was equally likely to occur after shapes in any triplet position and in either the attended or the unattended stream.

Participants—Thirteen undergraduate students and members of the University of Pennsylvania community (8 female, 5 male, aged 18–30) were tested after giving informed consent. Two subjects were replaced for low familiarization performance. In this and the subsequent experiments, all participants were native English speakers with normal or corrected-to-normal vision, and were either given course credit or a paid rate of $10/hr in exchange for participating.

Stimuli—In addition to the 12 shapes in each color set, a thirteenth shape was added to both color sets. This shape was identical for both sets but occurred in the set's designated color.

Familiarization Sequences—Stimuli were divided into the two color sets comprised of 12 shapes each, and grouped into four triplets just as in Turk-Browne et al. (2005) Experiment 3. However, in 24 random locations in each shape set, we inserted the thirteenth shape into the sequence (rather than repeating a shape as in the one-back cover task). This insertion was equally likely to occur after a triplet's first, second, or third shape. A total of 624 shapes were presented.

Procedure

Familiarization phase: Prior to testing, participants were shown the thirteenth shape in their assigned color set, and instructed to detect the appearance of this shape. Although this thirteenth shape would sporadically appear in both colors, they were reminded to only press a key when it appeared in their assigned color.

Implicit test phase: The test phase exactly followed the procedure as described in the General Methods. The (new) thirteenth shape did not appear as a test target.

Results and Discussion

During the familiarization phase, detection accuracy for the prespecified shape in its assigned color was at ceiling, 99.7% (*SD*= 1.2%). At test, accuracy, which was calculated as hits/(hits+misses), was 82% for the attended shapes and 85% for the unattended shapes. Detection accuracy at test did not differ based on stream (attended vs. unattended), $F(1,12) < 2.5$ or intratriplet position (first vs. second vs. third), $F(2,24) < 1$, nor did these factors interact, $F(2,24) < 1$.

For response latencies, there was a main effect of item position at test, $F(2,24) = 24.0$, $p < .01$, $\eta_p^2 = .67$, $\eta^2 = .04$[1], as well as a main effect of stream $F(1,12) = 9.11$, $p = .01$, $\eta_p^2 = .43$, $\eta^2 = .01$, although—critically—no interaction between these factors, $F(2,24) < 1.5$. These results do not match the findings reported in Turk-Browne et al. (2005), where there was an interaction between stream and position, indicating that observers only learned the attended shape sequences. Here, we see learning for both streams. We observed a main effect of position for the attended shape stream, $F(2,24) = 3.34$, $p = .05$, $\eta_p^2 = .22$, $\eta^2 = .02$, and a main effect of position for the unattended shape stream, $F(2,24) = 19.01$ $p < .01$, $\eta_p^2 = .61$, $\eta^2 = .07$.

Additionally, while Turk-Browne et al. (2005) observed a main effect of attention driven by speeded responses the attended stream, our main effect of attention reflects faster RTs for the unattended shape set. Planned follow-up comparisons indicate that the main effect between the two streams is driven by significantly faster RTs for the third position in the unattended stream (466 ms) than in the attended stream (485 ms), $t(12) = 2.95$, $p = .01$, $\eta_p^2 = .42$, $\eta^2 = .03$. Planned comparisons also indicate significantly faster RTs for the third position vs. the first position in the attended stream, $t(12) = 3.47$, $p = .005$, $\eta_p^2 = .50$, $\eta^2 = .03$, as well as in the unattended stream, $t(12) = 5.92$, $p < .01$, $\eta_p^2 = .75$, $\eta^2 = .10$ (Figure 2).

These results suggest that observers learned the regularities that structured the presentation of both attended and unattended shapes. This occurred despite the fact that we directed subjects' attention to only one stream, and that they had to suppress responses to the target shape when it appeared in the unattended stream. Interestingly, even though observers were only looking for one specific shape in one specific color—rather than the continuous process of updating and comparison necessitated by the one-back cover task—they still were able to extract the structure in which the target shape was embedded. However, the shape detection cover task may have required substantially less working memory load than the repetition

[1]Calculations for generalized eta squared (η^2) are described in Olejnik & Algina (2003)

detection cover task, since there was no requirement to update the contents of working memory with each new item. Thus, it is possible that observers had an abundance of attentional resources at their disposal in this experiment; this would allow the excess attention to “spill over” to the to-be-ignored shape set regularities in the other task (Lavie, 2004, 2010). In this case, referring to this shape set as “unattended” would be a misnomer. However, this may be the case even under the task conditions in Turk-Browne et al.’s (2005) Experiment 3. We will return to this possibility in the General Discussion.

Experiment 2: Reproducing an implicit signature of visual statistical learning

Results from Experiment 1 indicate that, when observers are exposed to a cover task that requires selective attention but not relational processing for one stimulus stream, observers learn the structure of both attended and unattended streams. This result is at variance with the conclusion of Turk-Browne et al. (2005) that selective attention alone is sufficient to modulate VSL. Thus, in Experiment 2, we returned to the original design of Turk-Browne et al. (2005) in order to ensure that we could replicate their results. This experiment tested the automaticity of VSL by manipulating attention to shapes of only one color during the familiarization phase with the repetition detection task, and then sequentially testing for learning of the shape regularities with an implicit response-time (RT) measure.

Method

Participants—Twenty-six undergraduate students and members of the University of Pennsylvania community (16 female, 10 male, aged 18–30) were tested after giving informed consent. Six subjects were replaced due to low performance on the familiarization task. Because this experiment is a direct replication of Turk-Browne et al.’s (2005) Experiment 3, and because direct replications require larger sample sizes than the studies they seek to replicate to have adequate power, we increased the sample size from the original study (n=12).

Familiarization Sequence—To allow for a repetition detection task during familiarization, in both color sets either the first or last shape in a triplet was randomly repeated 24 times. Following the Turk-Browne et al. (2005) design, there were 12 first shape repetitions and 12 third shape repetitions per color set. After interleaving the two color sets, an average of 0.88 unattended shapes separated the attended shapes from their respective repetitions (*SD* = 1.32).

Procedure

Familiarization phase: Participants were instructed to press a key whenever they saw the same shape in their assigned color set appear twice in a row. They were reminded that the consecutive repetitions might be occasionally interrupted by intervening shapes from the other color set, but to disregard these interruptions and to respond as if the intervening shapes did not appear.

Implicit test phase: The test phase exactly followed the procedure as described in the General Methods.

Results and Discussion

During the familiarization phase, observers completed the repetition detection cover task with 94% accuracy (*SD* = 6.3%). At test, accuracy was 83% for the attended shapes and 85% for the unattended shapes. Test target detection accuracy did not differ based on stream (attended vs. unattended), $F(1,25) < 1$, or intratriplet position (first vs. second vs. third), $F(2,50) < 1$, nor did these factors interact, $F(2,50) < 1$.

Turning to target detection latency data from the test phase, we observed a main effect of intratriplet position (first vs. second vs. third), $F(2,50) = 8.9$, $p = .0005$, $\eta_p^2 = .26$, $\eta^2 = .02$. However, there was no main effect of stream, $F(1,25) < 1$, and these factors did not interact, $F(2,50) < 1$. Had learning occurred more robustly in the attended stream, we would have expected to replicate the stream × position interaction reported by Turk-Browne et al. (2005). Additionally, we observed a main effect of position for the attended shape stream, $F(2,50) = 6.77$, $p = .002$, $\eta_p^2 = .21$, $\eta^2 = .03$, and a marginal main effect of position for the unattended shape stream, $F(2,50) = 2.95$, $p = .06$, $\eta_p^2 = .11$, $\eta^2 = .01$. Planned follow-up comparisons also reveal statistical learning for both shape streams. Reaction times for the third position shapes were significantly faster than for the first position shapes, and this pattern held for both the attended stream, $t(25) = 3.34$, $p = .003$, $\eta_p^2 = .31$, $\eta^2 = .05$, and for the unattended stream $t(25) = 2.67$, $p = .03$, $\eta_p^2 = .17$, $\eta^2 = .02$ (Figure 3).

Rather than exclusively learning the structure of the selected stimulus population, observers learned the patterns in the irrelevant stimuli as well. Thus, our results replicated the learning effect for the attended shape regularities reported in Experiment 3 of Turk-Browne et al. (2005), but not the lack of learning for the unattended shape regularities. Table 1 outlines the contrasts between these results, the Turk-Browne et al. (2005) findings, and the results from the similar paradigm used by Campbell et al. (2012), which we will return to in our General Discussion.

Experiment 3: Probabilistic Transitions

We observed learning of the statistical structure for both shape sets in Experiments 1 and 2 regardless of the experimental manipulation of attention. Given these robust learning effects, it is possible that our subjects' statistical learning had reached ceiling performance for both shape sets. Indeed, since the statistical regularities amongst the stimuli were perfectly deterministic in both shape streams, perhaps the patterns were relatively easy to learn. To mitigate ceiling performance and rule it out as a potential explanation for our lack of an attentional effect, we increased the difficulty of extracting the regularities by making the statistical relationships more complex. Perhaps the regularities in the unattended shapes are more sensitive to the stability of the statistical structure. If this were the case, the unattended shapes would be less likely than the attended shapes to withstand increased stochasticity if within-triplet transitional probabilities were decreased. To test this hypothesis, we again implemented Experiment 2 with a single modification to the familiarization phase. In this case, we retained the repetition detection cover task and modified the transitional probabilities between items in a triplet.

If the regularities from the unattended stream, though learnable, are more vulnerable to decreased structural stability, then the RTs might not differ for these shapes across triplet positions. In contrast, attention focused on shapes from the attended stream might counteract the deleterious effects of the added irregularities. Thus, the regularities in the attended stream might be less affected by the extra noise in the sequence structure, and therefore more likely to elicit the predicted RT differences between triplet positions as observed in Experiments 1 and 2.

Method

Participants—Twenty-five undergraduate students and members of the University of Pennsylvania community (16 female, 9 male, aged 18–30) were tested after giving informed consent. Nine subjects were replaced for low performance on the familiarization task.

Stimuli—Eighteen shapes were selected from the original 24 shapes. Nine were randomly assigned to the red shape set and another nine to the green shape set, resulting in three triplets per shape set. The reduced number of shapes allowed us to insert noise into the Experiment 3 sequence while matching the familiarization duration of Experiments 1 and 2.

Familiarization Sequences—Each of the six triplets was repeated 32 times and randomly intermixed with other triplets in its color set. However, in six of each triplet's 32 repetitions, one of the triplet shapes was replaced with a shape from another triplet from its same color set. This switch occurred twice for the shape at each of the three intratriplet positions. To further decrease the intact structure, we also added more shape repetitions, so that the first and third shape each repeat four out of the 32 times. Thus, the probability that a given shape in a triplet is preceded by its expected shape is .75, and the probability that the entire triplet is intact is .625, or 5/8. ABAB and AA/BB inter-triplet sequences were still excluded, and the first and third shape of a given triplet were never simultaneously repeated. Each color set again consisted of 312 shapes in total, and attended shapes were separated from their repetitions by an average of 0.96 intervening shapes from the unattended stream (SD = 1.33).

Interleaving—The counterbalancing and formation of the interleaved sequence matched the design of Experiment 2.

Procedure

Familiarization phase: Subjects performed the repetition detection task on one set of the stimuli. Other than the changes to the stimuli, the familiarization phase experimental procedure exactly matched Experiment 2. This experiment also lasted ten minutes; RT and accuracy were logged.

Test phase: For each color set, each of the nine shapes served as a test target six times, for 108 total trials. Each test trial stream consisted of 18 shapes, with of two repetitions of each of the three triplets from the test target's color stream, randomly intermixed. Other than these adjustments to accommodate the reduced number of triplets per color set, the test procedure replicated the test phase from Experiment 2 and lasted approximately 15 minutes.

Results and Discussion

Participants satisfactorily completed both tasks with high accuracy, 94.7% (SD= .05) for the familiarization task and at test: 81.1% (SD= .07) and 80.0% (SD= .07) for the attended and unattended triplets, respectively. Although there was no main effect of condition (attended vs. unattended) on test accuracy, $F(1,24)<1$, or item position (first vs. second vs. third) $F(2,48)< 2.5$, in target detection accuracy at test, there was an interaction of these factors, $F(2,28)= 3.44$, $p< .05$, $\eta_p^2= .13$, $\eta^2= .04$ (Figure 4). Planned follow-up comparisons suggest that this effect is driven by disproportionately erroneous responses in detecting the first position shapes in the unattended stream: Accuracy was greater for the third position than for the first position only in the unattended stream, $t(24)= -2.34$, $p<.05$, $\eta_p^2= .19$, $\eta^2= .10$. Additionally, accuracy for first position shapes was greater for attended versus unattended shapes, $t(24)= 3.18$, $p< .01$, $\eta_p^2= .30$, $\eta^2= .16$.

Turning to reaction time data during the test phase, there was a main effect of item position in response latencies, $F(2,48)= 11.2$, $p<.01$, $\eta_p^2= .32$, $\eta^2= .02$, although no main effect of stream $F(1,24)<1$, and no interaction between these factors, $F(2,48)<1$. We observed a main effect of position for the attended shape stream, $F(2,48)= 4.67$, $p= .01$, $\eta_p^2= .16$, $\eta^2= .02$, and in the unattended shape stream, $F(2,48)= 8.58$, $p= .001$, $\eta_p^2= .26$, $\eta^2= .03$. Planned follow-up comparisons reveal that RTs were faster for the third position than for the first position for both the attended, $t(24)= 2.87$, $p<.01$, $\eta_p^2= .26$, $\eta^2= .02$, and unattended, $t(24)= 4.14$, $p<.01$, $\eta_p^2= .41$, $\eta^2= .03$, shape streams (Figure 5).

The pattern of results largely resembles what we found under our previous experimental conditions. In this case, decreasing the transitional probabilities between shapes decreased VSL efficacy in neither the attended nor unattended shape stream. This result suggests that even when the statistical structure is less deterministic than in Experiments 1 and 2, observers can still learn the triplet regularities, and this process is not modulated by our attentional manipulation.

Experiment 4: Measuring learning with an explicit test

Our results consistently indicate that observers learned the regularities in the unattended triplets, as manifested by speeded RTs for the third triplet position in both shape streams. While this must be partly due to our various familiarization tasks, it may also be impacted by our assessment of learning during the test phase. The majority of past studies on VSL measured learning via explicit familiarity judgments in a two-alternative forced choice task. We measured VSL efficacy using RTs. The latter method might be a more sensitive measure of learning, while familiarity judgments may not reflect the full extent of retained information. If the results from the explicit test indicate learning for the attended but not unattended regularities, then the evidence of learning for unattended regularities may be more sensitive to implicit performance measures.

Method

Participants—Twenty-four undergraduate students and members of the University of Pennsylvania community (12 female, 12 male, aged 18–30) were tested after giving informed consent. Two subjects were replaced due to low familiarization task performance.

Procedure

Familarization Phase: Subjects performed the repetition detection task on one set of the stimuli, identical to the familiarization phase procedure in Experiment 2. The average number of intervening items between the attended shapes and their repetitions was 0.95 (*SD* = 1.47).

Explicit Test Phase: Subjects viewed two triplet sequences per trial. Each of these three-shape sequences was presented with the same manner and timing as in the familiarization phase, and were temporally segmented by a 1,000 ms pause. All shapes were presented in black, and one triplet was the "true" triplet, while the other was the "foil" triplet. The true triplet sequence was derived from either of the red or green triplets from familiarization stream. The foil sequence was constructed by taking three shapes from the same color stream as the true triplet, although each of these three shapes were derived from three different triplets: The first shape was the first shape from one triplet, the second was the second from another triplet, and the third was the third from yet another triplet. Thus, the foil triplets preserved positional information for the shapes, but not transitional information. The presentation of true and foil triplets, as well as whether the triplets originally came from the green or red color set, were counterbalanced across trials.

After the presentation of the two triplets, subjects pressed a key to identify whether the true triplet was presented first or second, in an unspeeded manner. Specifically, they were instructed to identify which three-shape sequence seemed more familiar based on the familiarization sequences (see Figure 1b). Subjects did not receive feedback on their responses. Each of the eight true triplets were tested eight times, appearing twice with each of four foil triplets from the true triplet's same original color set. These 64 trials were presented in a random order for each subject.

Data Analysis—Here, the measure of statistical learning was subjects' accuracy in detecting true triplets apart from their foils. This discrimination accuracy was calculated separately for triplets that were originally from the attended versus unattended color set.

Results and Discussion

Subjects performed the familiarization task with 92.1% accuracy (SD= .10). During the explicit task, subjects were significantly above chance (50% accuracy) for detecting the true triplets over the foil triplets, both for triplets from the attended stream, with 61.5% accuracy, $t(23) = 3.03$, $p = .006$, $\eta_p^2 = .29$, $\eta^2 = .17$, and 55% accuracy for triplets for the unattended stream, $t(23) = 2.10$, $p = .05$, $\eta_p^2 = .16$, $\eta^2 = .16$ (Figure 6). Additionally, the difference between attended and unattended test performance was not significant, $t(23) = 1.59$, $p = .13$, $\eta_p^2 = .10$, $\eta^2 = .06$. In contrast, Turk-Browne et al. (2005) report 77% accuracy for attended stimuli and 49% accuracy for unattended stimuli; the latter was indistinguishable from 50%

chance. The differences in subject performance between Turk-Browne et al.'s (2005) Experiment 1b and this direct replication are detailed in Table 2.

The result of Experiment 4 extends the pattern of findings we have accumulated throughout our study of VSL. Here, learning for the unattended regularities, in addition to the attended regularities, is observed even with explicit performance measures. We surmised above that learned information about the unattended stream might be inaccessible to awareness, which would explain why the implicit RT measure might show learning in the unattended stream while explicit familiarity judgments might not. Our results are consistent with such a deficiency in the explicit test: The accuracy advantage in the attended relative to the unattended stream approaches significance at p=.13. However, explicit familiarity judgments still reflect VSL for both stimulus sets regardless of the attentional manipulation (although subjects do not learn either stream as well as the subjects in Turk-Browne et al. (2005) learned the attended stream).

Simulation of VSL Effects—The interpretation of the experiments and analyses described above relies upon calculating a statistic over a small sample of subjects and comparing it to a critical value. This is a standard approach in psychology, but when interpreting it as "non-replication," a caution is in order: As Gelman & Stern (2006) put it, "The difference between 'significant' and 'not significant' is not itself statistically significant." Put another way, it is difficult to be sure that the observation by Turk-Browne et al. (2005) of a Condition ´ Position interaction significant at p= .05 is different in some meaningful way from our null results with higher p values. In particular, our data might contain weak evidence for an interaction that is impossible to discern within the individual samples.

To address this issue, we pooled the data from the 64 subjects who completed the implicit test phase in Experiments 1–3. We constructed three distributions of statistics from 2000 random samples of 12 subjects each—the same number reported in Turk-Browne et al. (2005), Experiment 3. We then compared the observed distribution to draws from the appropriate null distribution, allowing us to assess whether our aggregated data contained evidence for a Condition ´ Position interaction to which the individual studies were insensitive.

For each of the 64 subjects in Experiments 1–3 reported above, we calculated six mean RTs (attended/unattended ´ triplet position 1, 2, or 3) as described above. For each sample, we selected 12 subjects and calculated three statistics on those subjects' RTs: a t statistic for Positions 1 versus 3 separately for the attended and unattended triplets, and the F statistic for the Condition ´ Position interaction. We drew 2000 such samples with replacement. For each of those 2000-item distributions, we calculated the likelihood of a significant result at p= .05, corresponding to $t(11)$= 1.80 or $F(1,11)$= 3.49. Additionally, we used the Kolmogorov-Smirnov test to compare the simulated distribution to a 2000-item draw from the corresponding null distribution. We used the same test to compare the simulated t distributions to one another.

Our simulated *F* distribution yielded a Condition ´ Position interaction 62 times out of 2000, a probability of 0.03. Thus, if anything, our observations show less of a tendency toward that interaction than one would expect by chance. Figure 7a plots our simulated *F* distribution (histogram) overlaid by the probability density function for the *F* distribution (red line), scaled to 2000 samples. The two distributions look highly similar; notably, our simulated *F* statistics are more likely to assume low values, and less likely to assume high ones, than the null distribution. The difference between the distributions is small, but highly significant by Kolmogorov-Smirnov test (D= .14, p<2.2×10^{-16}) (Figure 8a).[2],[3]

By contrast, our simulated *t* distributions, quantifying the basic learning effect in each condition, are substantially different from the null distribution. In both attended and unattended conditions, we were highly likely to observe a significant *t* statistic in the predicted direction (RTs for Position 1 > Position 3); the probability was 0.71 for the attended condition and 0.81 for the unattended condition. Figure 6 plots the probability density function of the *t* distribution (red line) overlaid on simulated *t* statistics for the attended (Figure 7b) and unattended (Figure 7c) conditions. The differences between both distributions and the null *t* distribution are highly significant by Kolmogorov-Smirnov test (D=0.78 and 0.82 for attended and unattended conditions respectively, p<2.2´10^{-16}) (Figures 8b and 8c). Note that, although all three differences are significant, the *D* statistic for the simulated *F* distribution is very different from those of the simulated *t* distributions. The simulated *t* distributions are also significantly different from one another (D=0.16, p<2.2´10^{-16}), though the *D* statistic is much smaller than those for the differences between the simulated *t* distributions and the null *t* distribution.

General Discussion

Across several experiments and 88 total subjects, we consistently find that our subjects learn transitional probabilities in temporally presented visual stimuli from both attended and unattended stimuli. This is true when we change the cover task from repetition detection to detection of a target shape that could appear in either stream; when we reduce the within-triplet transitional probabilities; and when we assess learning with an explicit familiarity judgment rather than the implicit RSVP measure. Pooling our subjects and simulating thousands of experiments shows that not even a weak effect of attention is present in our data.

Is attention, then, irrelevant to VSL? We are reluctant to make that conclusion; a great body of work has convincingly demonstrated the influence of attention on associative learning (Mackintosh, 1975; Pearce & Hall, 1980; Kruschke, 2005), category learning (Maddox, Ashby, & Waldron, 2002; Love, Medin, & Gureckis, 2004; Rehder & Hoffman, 2005), reinforcement learning (Dayan, Kakade, & Montague, 2000; Daw & Touretzky, 2001; Roelfsema & van Ooyen, 2005), and word learning (Smith, Colunga, & Yoshida, 2010). While the present findings do not suggest that attention is completely unnecessary for VSL,

[2] 2.2×10^{-16} is the smallest number that can be represented in R.

[3] The *D* statistic is the maximum difference between the empirical distribution functions (EDF) of the observations, where *EDF*(*x*) is the proportion of elements less than or equal to *x* (and thus a nondecreasing function mapping *x* to [0,1]). Thus, D=0.14 means that there is an observation for which the difference between the EDFs is 14% of the number of observations.

our results indicate that VSL can also operate on task-irrelevant aspects of the input. Below, we consider the limiting conditions on the relevance of attention to statistical learning.

Attention and Statistical Learning

Several studies have examined the impact of attention on statistical learning in both visual and auditory domains. Unlike the present work and that of Turk-Browne et al. (2005), the majority of this research has manipulated attention via simultaneous presentations of the stimulus regularities and the competing stimuli. For instance, in the visual domain, results from two separate studies suggest that attention is necessary for learning spatial relations among stimuli. In one such study, Jiang & Chun (2001) manipulated attention by presenting some of the distractors in a color that the subject was instructed to ignore; they reported that spatial VSL (i.e., learning repeated configurations in visual search displays) occurs only in the presence of attention. Additionally, Baker, Olson, & Behrmann (2004) observed that attention modulates the effect of perceptual grouping on spatial VSL. Subjects were instructed either to attend to both locations of two shapes on a screen or to just one of the two locations. Subjects could learn whether the shapes co-occurred when they attended to both locations or when the shapes were connected by a line; however, they could not learn the co-occurrence if they attended to only one location and the shapes were not connected. Both studies only observed spatial VSL for attended stimuli or locations when attentional demand was high, namely, when competitors and to-be-attended regularities were displayed at the same time.

The influence of attention on statistical learning is not restricted to spatial VSL; attentional effects have been found for auditory SL as well. In a study by Saffran et al. (1997), when subjects' attention was diverted away from the statistical regularities amidst a distractor task, learning efficacy suffered. In this experiment, adults and 6- and 7-year-old children performed a picture-drawing task while recordings of auditory statistical regularities played in the background. Both child and adult subjects extracted the regularities, but their learning was relatively weak, with adults judging "word" sequences as more familiar than "nonwords" 58.6% of the time and children doing so 59.2% of the time, after 21 minutes of exposure.[4] Learning improved when Saffran et al. (1997) doubled the exposure to 42 minutes; performance on the unattended auditory stream increased to 73.1% in adults and 68.3% in children.

Work by Toro, Sinnett, & Soto-Faraco (2005) reiterates the role of attention in auditory SL. When subjects listened passively to a speech stream identical to that used by Saffran et al. (1996), they discriminated statistically-defined "words" from nonwords at a rate of about 70%; however, when they had to perform a one-back task on a concurrently presented stream of familiar nonlinguistic noises (Experiment 1) or line drawings (Experiment 2), or detect a pitch change in the speech stream (Experiment 3), performance declined, sometimes to chance levels. Notably, though, the required attentional redistribution was always

[4]In contrast, Gebhart, Aslin, & Newport (2009) report 80% accuracy for a five-minute exposure to a more complexly structured language, and various nonlinguistic statistical learning tasks yield 70–95% accuracy for exposures no longer than 22 minutes (Fiser & Aslin, 2002a; Creel, Newport, & Aslin, 2004). However, in these studies, subjects were instructed to attentively watch or listen to the stimulus presentation, and there were no competing stimuli or additional tasks.

concurrent to the task—that is, subjects were directed to attend to noises, pictures, or pitch rather than the simultaneously presented unfamiliar syllabic information. This is not the case for our VSL task, in which attended and unattended stimuli are interleaved rather than concurrent, and both stimulus sets are equally unfamiliar.

Additionally, Pacton & Perruchet (2008) reported a series of experiments showing that attention modulates processing of adjacent and nonadjacent dependencies when these cross-stimulus relations are task-relevant. In general, subjects are less apt to learn nonadjacent than adjacent dependencies; Pacton & Perruchet (2008) showed that instructing subjects to do a task involving nonadjacent stimuli (subtracting the digits on either side of a target digit) led them to learn nonadjacent dependencies more readily than a task involving only adjacent stimuli (subtracting the two digits following a target digit). The reverse was also true: Subjects who processed only nonadjacent digits did not notice relationships between adjacent digits. The implications of this work for ours are not clear, since our subjects were instructed to process stimuli that were adjacent within the attended stream—which were sometimes genuinely adjacent, but sometimes separated by varying numbers of elements from the unattended stream.

These experiments share a feature: Regardless of whether the statistical relationships to be learned were spatial or temporal, attention was always manipulated with concurrently presented distractors. This is in contrast to our work and that of Turk-Browne et al. (2005), in which an isolated stimulus is attended or ignored. Emberson, Conway, & Christensen (2011) likewise exposed subjects to interleaved presentations of visual (i.e., shape) and auditory (i.e., syllable) regularities, with stimuli in one modality to be attended and those in the other to be ignored. In Experiment 2, they found that performance of a concurrent one-back task on the auditory stimuli successfully suppressed learning of the statistical relationship between the visual stimuli, suggesting that selective attention to a sensory modality can modulate statistical learning.

Finally, Campbell, Zimerman, Healy, Lee, & Hasher (2012) provide the closest replication of Turk-Browne et al. (2005) that we know of, and the only other example of isolated, interleaved presentations of to-be-attended and to-be-ignored stimulus regularities of exclusively visual stimuli. Like Turk-Browne et al. (2005) Experiment 3, these authors report a Condition ´ Position interaction in young adult subjects directed to perform the same cover task on line drawing stimuli presented in red or green. They find no such interaction in older adults, who are slower overall but show speeded reaction times for later serial positions in both attended and unattended streams. Campbell et al. (2012) infer that older adults are less able to filter out irrelevant information. Their task differs from that reported by Turk-Browne et al. (2005) only in the use of line drawings of familiar objects for stimuli.

Excepting Campbell et al. (2012) and Emberson et al. (2011), a common theme in this literature is the relevance of selective attention when the to-be-attended and to-be-ignored stimuli are simultaneously presented. Saffran et al. (1997) had subjects draw while listening; Toro et al. (2005) had subjects perform secondary tasks while listening; Pacton & Perruchet (2008) had subjects focus on adjacent or nonadjacent dependencies while the other type of dependency was also present. The attentional manipulation shared by the present work and that reported by Turk-Browne et al. (2005) is atypical in that subjects are presumed to be suppressing attention to a single stimulus, without a contemporaneous competitor for attentional resources. However, the decision to ignore a stimulus must be made on the basis of an attribute of that very stimulus, necessitating a certain amount of processing.[5] In light of this fact, the failure of this particular attentional manipulation to modulate learning is perhaps not surprising. Although subjects have no particular incentive to process the unattended stream, the very presence of statistical information can attract attention (Chun & Jiang, 2002; Zhao, Al-Aidroos, & Turk-Browne, 2013), potentially by reshaping object representations in the hippocampus (Schapiro, Kustner, & Turk-Browne, 2012); thus, especially in the absence of a competitor for attentional resources, we might expect the structure present in the unattended stream to be attended and learned.

Additional research could more strongly test the influence of selective attention and the role of single versus joint stimulus presentations by further modifying the familiarization phase. For instance, the issue of isolated versus simultaneous events could be addressed by presenting both attended and unattended shape sequences on the screen together. However, a shared spatial configuration potentially creates visual processing asymmetries between unattended and attended stimuli, such that it would be unclear if an absence of learning for unattended regularities would be due to lack of attention or lack of visual processing or acuity (see p. 554 in Turk-Browne et al., 2005, for a further discussion of this issue). Instead, the role of attention during isolated presentations could be tested by enhancing the salience of the attended stimuli, or by decreasing the perceptual similarity between the attended and unattended stimulus sets.

Moreover, attention may be more likely to modulate VSL in an environment where stimuli are more complex and ambiguous than the stimuli used in our experiments. In all of our familiarization procedures, there were only two competing stimulus populations, and they were clearly discernible and easily discriminable for the observer, in the absence of any other competing or irrelevant stimuli. Given that there were only two stimulus populations present in the task, perhaps the capacity to encode the regularities was not taxed enough to narrow focus to only the task-relevant regularities. Although we instructed subjects to ignore the task-irrelevant stimuli, we cannot confirm that we successfully manipulated attention. Future studies should examine VSL and selective attention effects in environments that contain multiple regularities amongst detail-rich stimuli that more closely resemble our everyday, real-life learning environments.

[5]The same is true of Experiment 3 of Toro et al. (2005), in which subjects must make a decision about the pitches of the presented syllables, where the syllables contain the statistical regularities. Thus, there is evidence that selective attention to one feature of an object (pitch) can interfere with processing another feature of that same object (syllable identity; but see Conway & Christiansen, 2006). However, Toro and colleagues never require subjects to make a decision based on syllable identity, the stimulus feature that contains the regularities. In contrast, in our work and the work of Turk-Browne et al. (2005), attention is focused on the relevant, statistical stimulus property: subjects must make a decision based on shape identity in the attended stream, and it is also the shape identities that contain the statistical structure. Thus, attention is focused on shape identity, and attention to this stimulus property might “spill over” to the task-irrelevant stimuli. If task set can influence the distribution of attention, as suggested by the results of Pacton & Perruchet (2008), that could account for differences between the paradigms. However, these explanations are speculative; targeted experiments would be required to confirm them.

Stimulus Effects on Temporal Statistical Learning

We have already reviewed work demonstrating the generality of statistical learning— spatial and temporal relationships among diverse types of visual and auditory stimuli are learnable. However, this does not mean that the nature of the stimulus has no influence on statistical learning. Conway & Christiansen (2005) showed that temporal relationships in auditory input were learned more efficiently than those governing visual and tactile stimuli. Conway & Christiansen (2006) demonstrated that statistical learning is not modality-independent; two artificial grammars can be learned simultaneously, without mutual interference, unless the items in the grammar are in the same dimension in the same stimulus modality (e.g., both sets of items are shapes or nonsense syllables, rather than shapes and colors, or syllables and tones). And Emberson and colleagues (2011) showed that presentation rate modulates the efficacy of learning in a stimulus-dependent fashion; relationships among auditory nonsense syllables were learned more effectively than relationships among shapes at a 375 ms SOA and 175 ms ISI, but the advantage reversed when the stimulus duration and ISI were doubled. The advantage for slow SOAs in VSL is corroborated by Turk-Browne et al. (2005), Experiments 1A and 1B, in which increasing the SOA from 400 to 1000 ms improved learning on the attended stream from 59% to 77%.

These results may bear on the replication of Turk-Browne et al. (2005) reported by Campbell et al. (2012). As mentioned above, Campbell et al. (2012) ran an experiment identical to that of Turk-Browne et al. (2005) except in that they used line drawings of objects, which were nameable (in particular, they used the stimuli from Snodgrass & Vanderwart, 1980, which are commonly used in studies of picture naming). Subjects might have used the names of the objects to determine whether to respond in the one-back cover task. We would not venture to guess whether names generated from visual information are more like visual or auditory stimuli in terms of the most effective presentation rate for learning; however, if they are more like auditory stimuli, presenting them at a rate most effective for visual stimuli should make for a harder learning task, in which the effects of a relatively weak attentional manipulation might be amplified.

The results of Emberson et al. (2011) also complicate our suggestion that competition between stimuli is necessary to suppress statistical learning via inattention. Intuitively, one might imagine that selective attention to color might more easily suppress processing of auditory information than that of visual information in the same location (i.e., shape). However, Conway and Christensen (2006) find that interleaved presentation of an auditory and a visual artificial grammar results in learning no worse than that of a single grammar in either modality. In fact, the only case in which they do observe interference is the one we employ—namely, the case in which both grammars are in the same dimension of the same stimulus modality (e.g., both shapes, both pure tones). However, in their experiments, no stimulus modality is ignored or emphasized over another. Meanwhile, Turatto, Galfan, Bridgeman, and Umiltà (2004) report that task-irrelevant information interferes more with a speeded discrimination task in a different sensory modality than in the same sensory modality. Thus, we remain uncertain about the comparative efficacy of within- versus cross-modal suppression by selective attention, and acknowledge that Emberson et al. (2011) may represent a case in which subjects selectively attend to one set of isolated events while ignoring another interleaved set.

Pairs and Triplets

Turk-Browne et al. (2005) and Campbell et al. (2012) report a feature of the unattended RTs that we observe as well: Second-position RTs are faster than first-position RTs. The difference between attended and unattended streams turns on the third-position items in both cases. This matter raises a broader question: In the attended condition, why should the third-position RTs be faster than the second-position RTs? The third-position items are no better predicted by the second-position items than the second-position items are by the first-position items. The consistent observation that the third-position RTs for attended items are the fastest suggests that the transitional information is not fully learned, and that the acceleration for third-position targets is influenced by partial information from first- and second-position items. However, other explanations are possible; perhaps the rapidity of the RSVP protocol prevents learned information from being fully leveraged for second-position items, or perhaps the context of a recent high-probability transition (first to second position) increases learning for a subsequent transition (second to third position).

Recent work from Bakarat and colleagues (2013) presents an additional explanation for the processing advantage of more predictable items. In their task, subjects were exposed to a temporal VSL paradigm similar to ours, but stimuli were grouped into pairs instead of triplets. After passively viewing the sequences, subjects performed a shape detection RSVP task, where second-position items were either preceded by their first-position items (match condition) or by another random shape (mismatch condition). While second-position items were detected faster than first-position items, this RT advantage was evident for both match and mismatch conditions. The authors speculate that the speeded response for second-position items may be due to differential item learning, rather than priming by their respective first-position item. Their interpretations could also apply to the speeded reaction times we observe for stimulus shapes from the third triplet position. Specifically, there may be greater sensitivity to later items relative to initial items as a result of statistical learning. More predictable items might be more salient because they receive more attentional resources and hence enhanced encoding of their internal representations, or because they co-occur with an implicit sense of familiarity.

Cohort Effects

Although our work and the work of Turk-Browne et al. (2005) were closely matched in experimental stimuli and procedure, they unavoidably differed in subject population. The two different subject populations may have approached the experiment with systematically different experimental strategies or abilities. The seven years separating data collection between the two studies have seen increased use of and access to technology, particularly visual displays on computer screens presented in rapid succession. Our modern-day college-age subject sample may have been better equipped to simultaneously attend to multiple information streams, and more susceptible to interfering information, than their 2005 counterparts.

Additionally, the learning differences between the two subject groups might reflect differences in overall working memory capacity, such that the cognitive load of the repetition detection task might have differed between the two groups. For instance, our subjects had high task performance during familiarization (94% and 92% for Experiments 2 and 4, respectively), relative to Turk-Browne et al.'s subjects on the same tasks (81% and 89% for Experiments 3 and 1b, respectively). The decreased performance observed by Turk-Browne et al. (2005) might indicate that their subjects had less available attentional resources during the repetition detection task. In contrast, if our subjects' high familiarization performance reflects as a relatively less taxed cognitive load, excess attention might have "spilled over," allowing subjects to attend to regularities in the "unattended" stream as well.

Methodological Differences

Our main experimental procedure differed from Turk-Browne et al.'s (2005) report in minimal but concrete ways. For instance, we used the same shape triplets for all subjects, whereas Turk-Browne et al. (2005) randomly generated the triplets for each subject. The latter choice was in efforts to avoid the highly unlikely possibility that some triplets are easier to learn than others by virtue of the randomly assigned shape configurations. Additionally, Turk-Browne et al. (2005) restricted the presentation of new shapes such that the number of items remaining in each color could not differ by more than 6. We used a criterion that we thought was identical but is in fact, on reflection, slightly different: We restricted runs of a single color to length 6. This permitted us to have longer runs skewing toward one color; for example, starting with the same number of shapes in each color, we could present 6 red, 1 green, 6 red, whereas Turk-Browne et al. (2005) could not (since the result would be 10 fewer red than green shapes remaining). If anything, though, this variation should have caused us to have more, rather than fewer, long runs of single colors. However, if our randomization for some reason selected for shorter runs of the unattended color between repetitions in the attended color, we agree that it might have contributed to the higher familiarization accuracy in our study versus the Turk-Browne et al. (2005) study.

The practice phase also differed from Turk-Browne et al. (2005) Experiment 3. Before beginning the experiment, our subjects were exposed to a stream of 30 shapes that randomly alternated between green and red shapes, with occasional immediate or sporadic shape repetitions. These were the same shapes used in the experiment proper, but not presented in their triplet configurations. In contrast, Turk-Browne et al. (2005) do not report that their subjects received a practice phase.

In light of the close correspondence between our work and the work of Turk-Browne et al. (2005), it is difficult to account for the divergence among our results. We have offered a number of reasons that the documented influence of attention in other work might not be relevant in the context of the present paradigm. However, since our Experiments 2 and 4 are direct replications of Turk-Browne et al.'s (2005) Experiments 3 and 1B, it is difficult to explain the basic contradiction between their observed effect of attentional modulation, versus the VSL we observed regardless of attention.

While we were unable to fully replicate the findings of Turk-Browne et al. (2005), our results underline the importance of attempting to do so. In fact, we were able to successfully replicate some central aspects of the original study, such as the evidence of learning on the implicit RT measure developed by Turk-Browne et al. (2005). We report the results above with confidence that they reflect what we observed in several direct replications of the work of Turk-Browne et al. (2005), but with all due caution as to whether they capture the true size of the effect any more faithfully than the initial work. Even the most robust empirical effects will not always be large enough to license rejection of the null hypothesis; random sampling is expected to yield at least some nonsignificant results when experiments are carried out correctly and fully reported (Francis, 2012). Conversely, even a true effect of size zero may be distributed such that some samples reject the null hypothesis. We suspect that our much larger sample provides the better estimate of the true effect of attention in this VSL paradigm, but only more replications will supply a decisive verdict.

The present research does not conclusively determine the role of selective attention in VSL. Nevertheless, these results demonstrate that various modifications to the stimulus presentation can limit the relevance of selective attention. In fact, in the absence of competing stimuli, VSL can robustly operate over stimuli that subjects have been directed to ignore.

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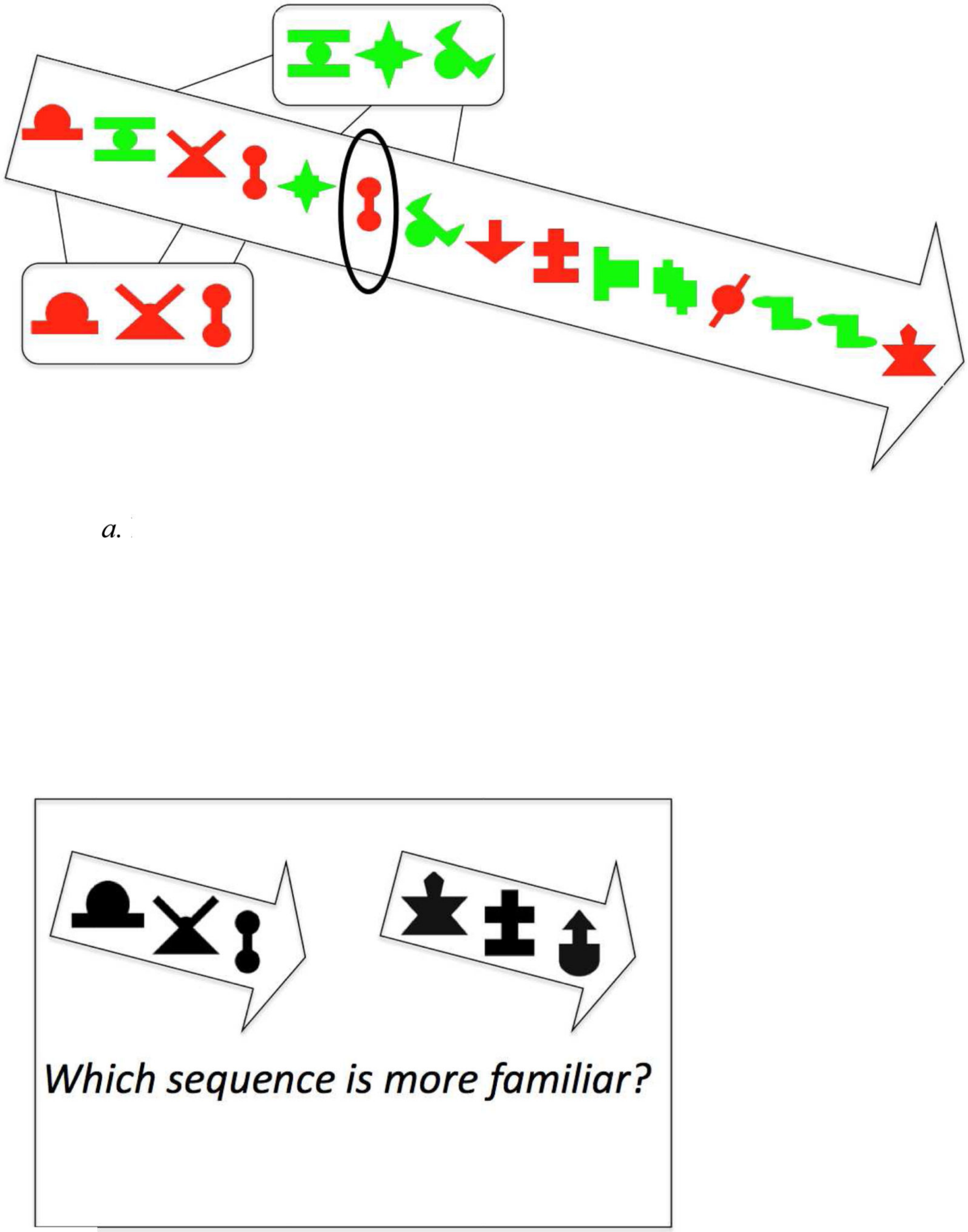

a.

b.

Figure 1.

a. Example of the familiarization phase in Turk-Browne et al. (2005) Experiment 3, depicting shape triplets (in boxes) and the interleaved stimulus presentation (in arrow). Each shape is presented in isolation with a 1,000 ms SOA and 200 ms ITI. Both color streams are comprised of four unique triplets and sporadic repetitions of the triplets' third shapes. To manipulate selective attention, observers only respond to shape repetitions in one of the two stimulus sets; circled is a shape presentation that should elicit a key-press response.

b. Example of the two-interval forced-choice familiarity judgment in Turk-Browne et al. (2005) Experiment 1B. Each shape appears in isolation, in two groups of three shapes each. Stimulus presentation duration matches the familiarization phase. Presentations of the two sequences are separated by a 1,000 ms pause. Observers select the more familiar sequence, based on the presentation they observed during the familiarization phase. The true triplet (left) matches a sequential ordering from the red shapes in the learning phase, while the foil triplet (right) is comprised of three shapes that were also originally red, but never occurred in this ordering during familiarization.

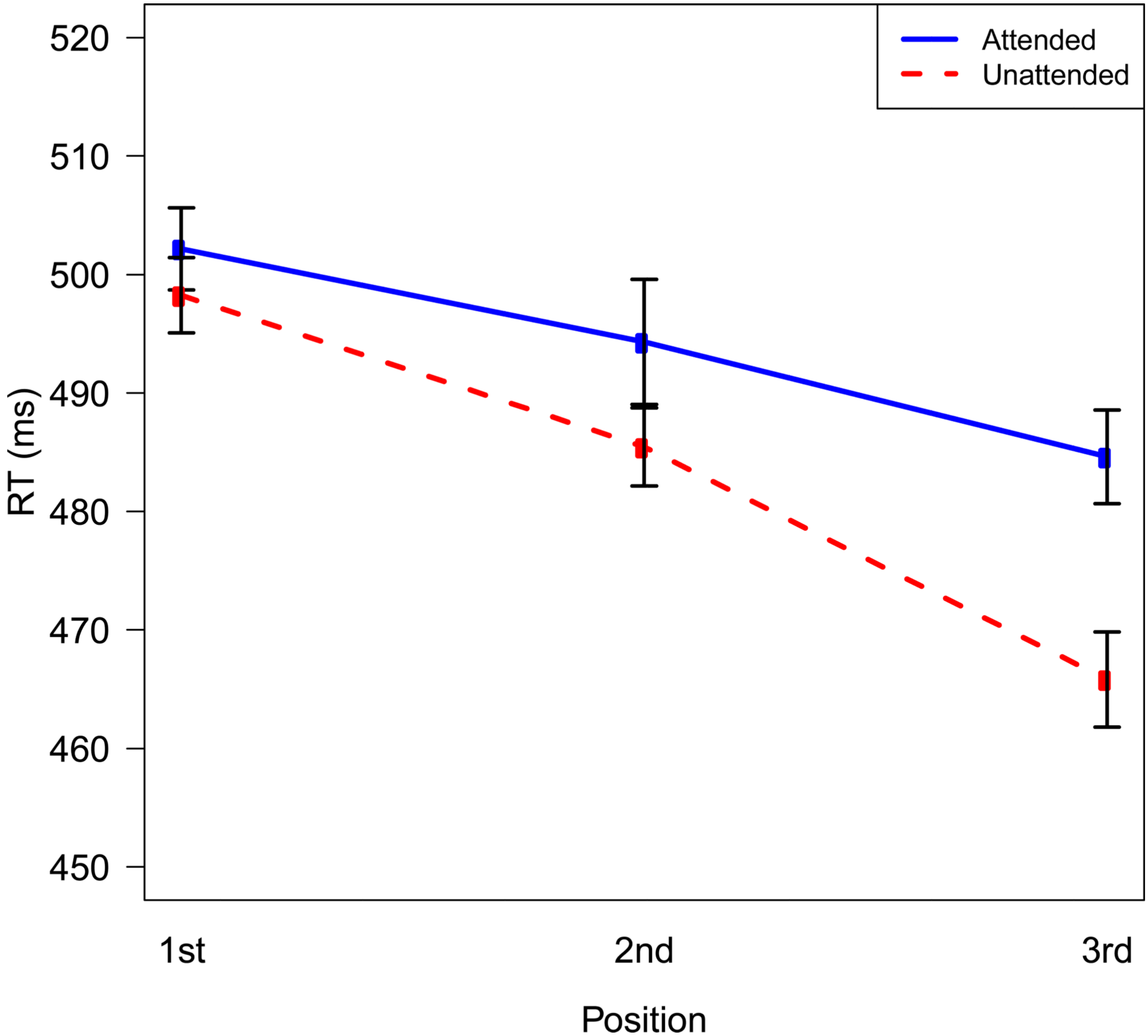

Figure 2.
Implicit test results from Experiment 1. Response times for detecting a pre-specified target in the implicit test RSVP task for attended (blue solid) and unattended (red dashed) shapes, separated by shapes' original triplet position from familiarization. Error bars reflect within-subject standard errors.

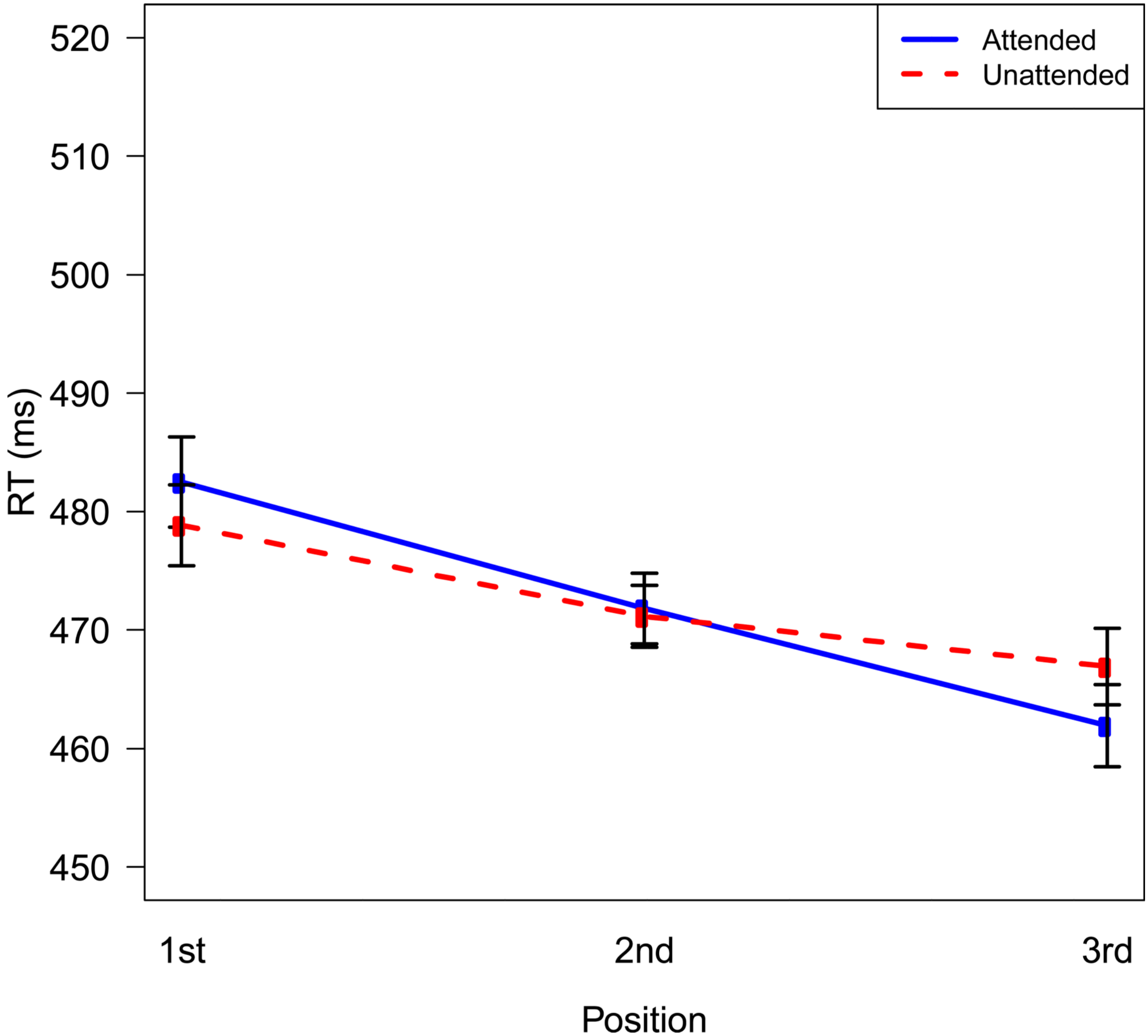

Figure 3.
A direct replication of Turk-Browne et al. (2005) Experiment 3. Response times from implicit RSVP test, separated by original triplet position. Error bars correspond to within-subject standard errors.

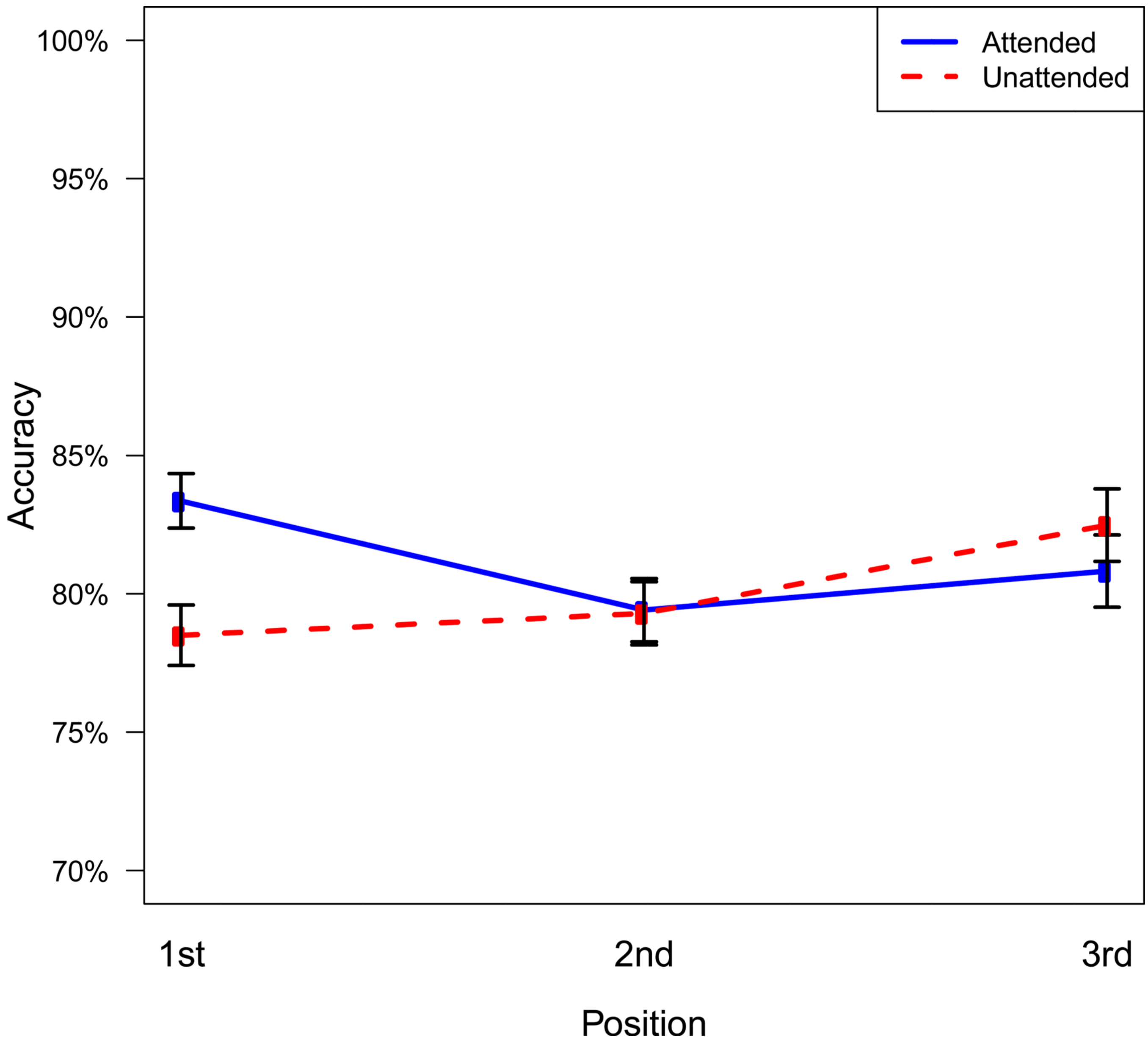

Figure 4.
Implicit test results for Experiment 3. Accuracy (i.e., hit rate) for detecting a prespecified shape during an RSVP task. Error bars correspond to within-subject standard errors.

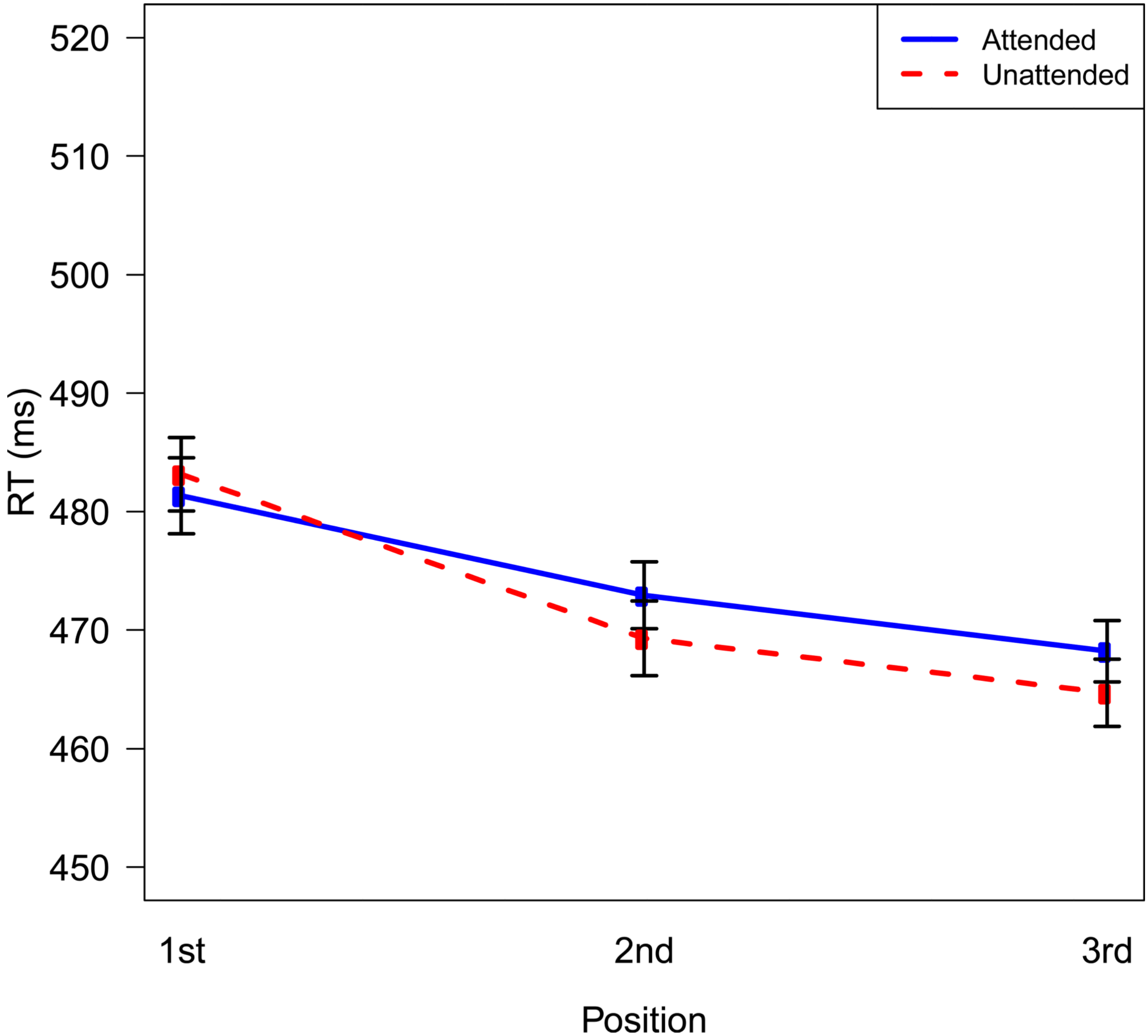

Figure 5.
Implicit test results for Experiment 3. Response times for detecting a prespecified shape during an RSVP task. Error bars correspond to within-subject standard errors.

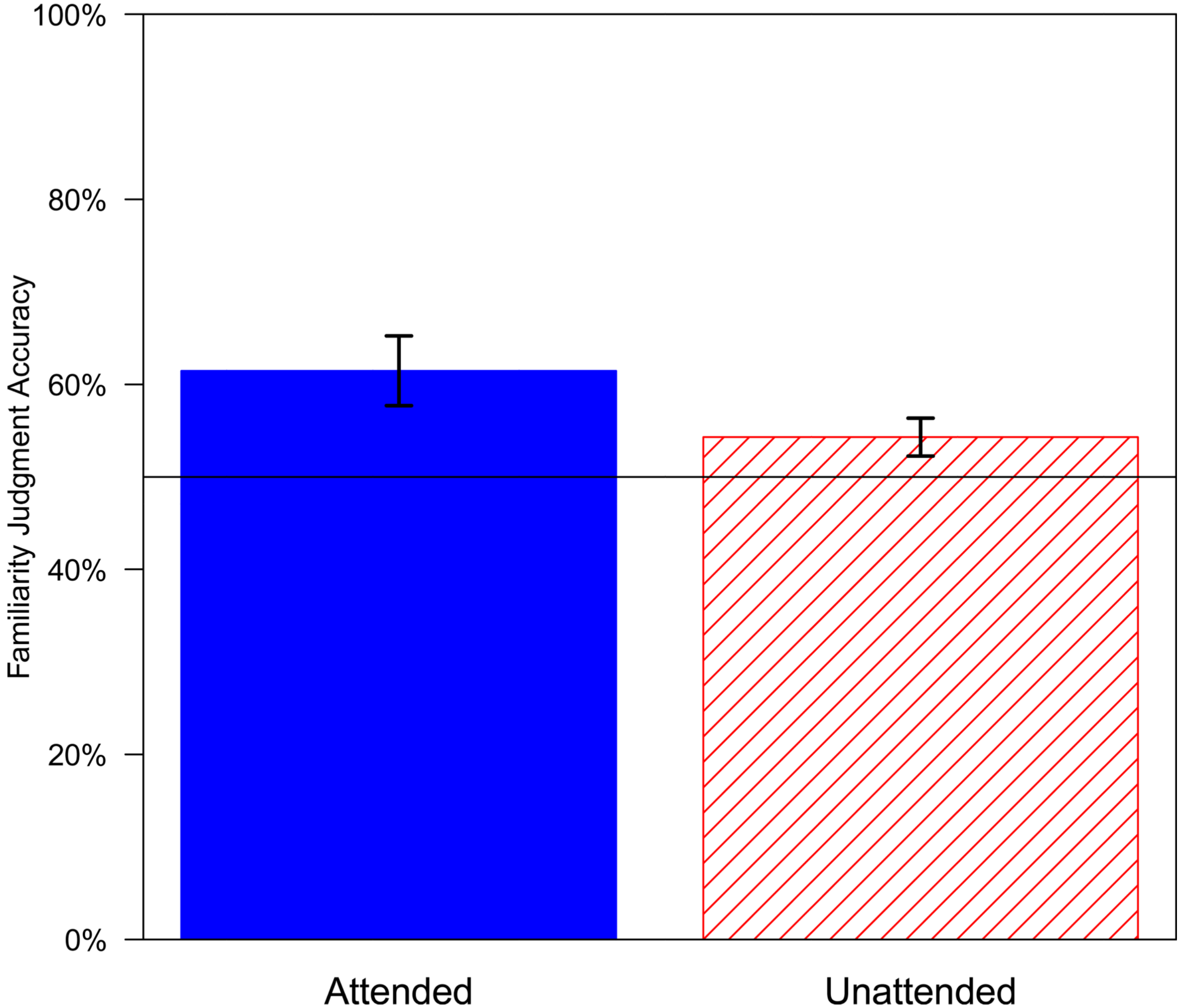

Figure 6.
A direct replication of Turk-Browne et al. (2005) Experiment 1B. Accuracy for discriminating true triplets from foil sequences in a two-interval forced-choice familiarity judgment. Black line indicated chance performance. Discrimination accuracy is above chance for true triplets from both attended and unattended stimulus sets.

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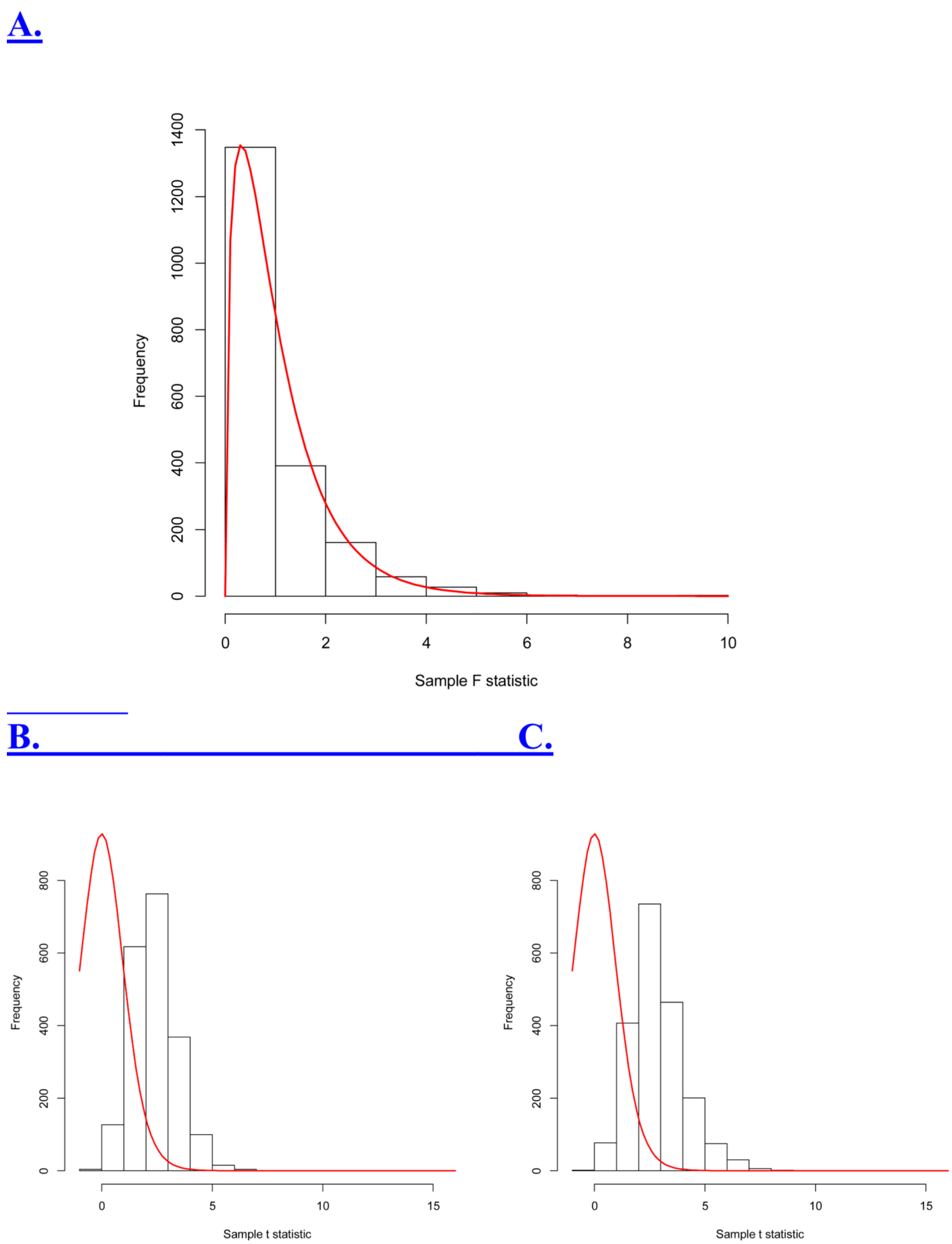

Figure 7.

Simulation results. Probability density function of the *t* distribution is shown by red line. (A). Histogram representing simulated *F* distribution for 2,000 samples. Red line reflects the probability density function for the *F* distribution. Note that the simulated and null *F* distributions look very similar. (B). Histogram of simulated *t* statistics for the attended stimuli. (C). Histogram of stimulated *t* statistics for the unattended stimuli.

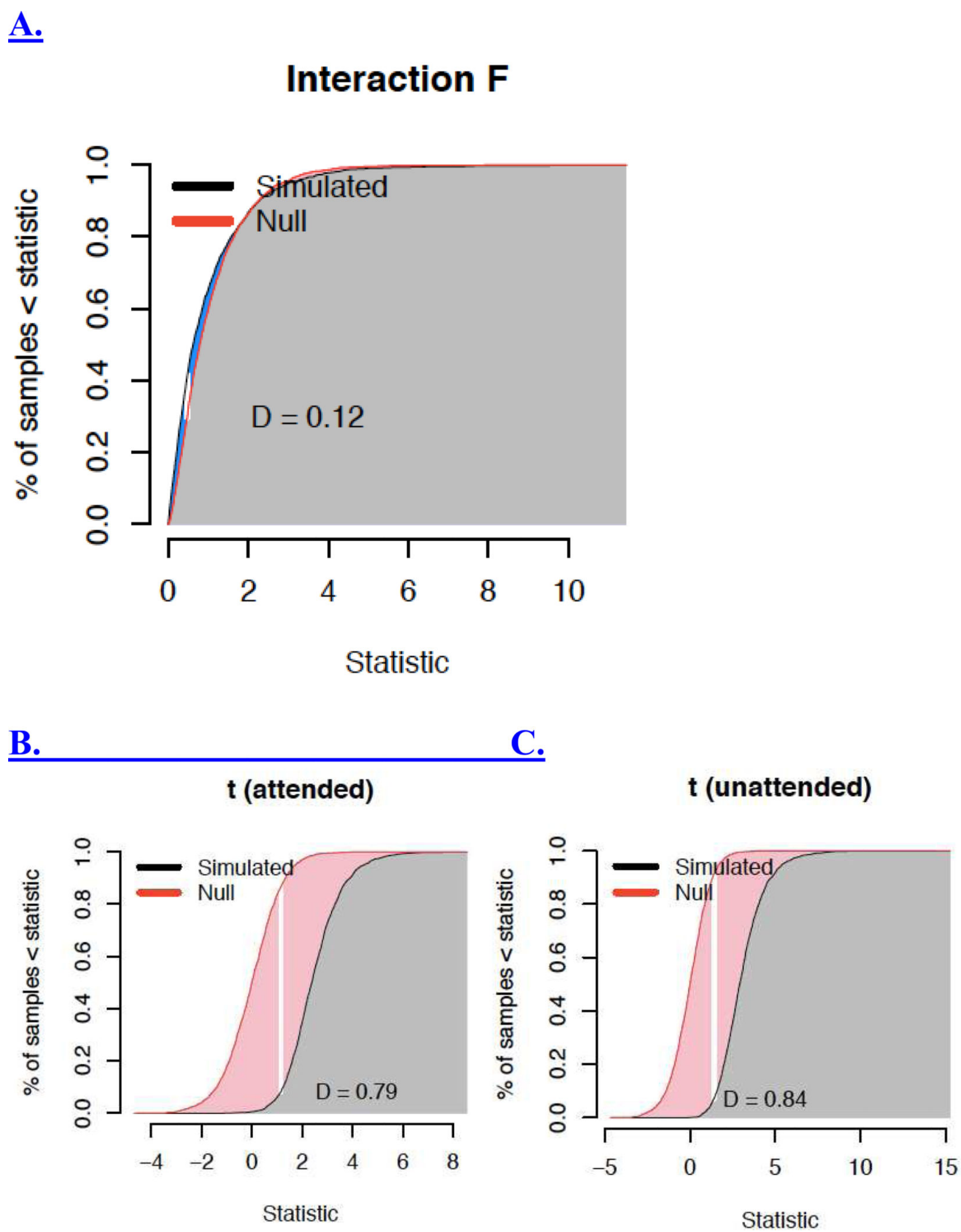

Figure 8.

Kolmogorov-Smirnov *D* statistics from the simulation results. The white line represents the maximum separation between the empirical distribution functions, which gives rise to the *D* statistic in each case. (A). Percentage of samples for each *D* statistic for the *F* distribution. Note that the white line indicating maximum separation is barely visible because the null and simulated distributions are very close. (B). *D* statistics for the *t* statistics for the attended stimuli and (C) *D* statistics for the *t* statistics for the unattended stimuli.

Table 1

Implicit Experimental Paradigm: Comparison of Results

-		**Experiment 2**	**Turk-Browne et al. (2005) Experiment 3**	**Campbell et al. (2012)**
-	**N Subjects**	**26**	**12**	**24**
Accuracy	Familiarization (*SD*) Attended Test Unattended Test	94.1 (*6*) 83 85	80.9 (*9.1*) 96.6 96.2	97.1 (*4.3*) 95.8 98.6
Test (RT)	Attention Main Effect Position Main Effect Attention x Position Interaction	$F(1,25) < 1$ $F(2,50)= 8.9$, $p= .0005$, $\eta 2p= .26$ $F(2,50)= 0.74$, $p= .48$, $\eta 2p= .03$	$F(1,11)< 1$ $F(2,22)= 2.25$, $p= .13$, $\eta 2p= .17$ $F(2,22)= 3.49$, $p= .048$, $\eta 2p= .24$	$F(1,23) < 1$ $F(2,46)= 3.64$, $p< .05$, $\eta 2p= .14$ $F(2,46)= 5.81$, $p< .01$, $\eta 2p= .20$
Attended Test (RT)	Position Main Effect Position 1 vs. 2 Position 2 vs. 3 Position 1 vs. 3	$F(2,50)= 6.77$, $p= .002$, $\eta 2p= .21$ $t(25)= 2.067$, $p= .05$, $\eta 2p= .15$ $t(25)= 1.83$, $p= .08$, $\eta 2p= .12$ $t(25)= 3.34$, $p= .003$, $\eta 2p= .31$	$F(2,22)= 5.71$, $p= .01$, $\eta 2p= .34$ $t(11)= 1.94$, $p= .039$, $\eta 2p= .25$ $t(11)= 1.97$, $p= .038$, $\eta 2p= .26$ $t(11)= 2.79$, $p= .009$	$F(2,46)= 7.99$, $p< .01$, $\eta 2p= .26$ $t(23)= 1.74$, $p= .095$ $t(23)= 2.17$, $p= .05$
Unattended Test (RT)	Position Main Effect Position 1 vs. 2 Position 2 vs. 3 Position 1 vs. 3	$F(2,50)= 2.96$, $p= .01$, $\eta 2p= .11$ $t(25)= 1.56$, $p= .13$, $\eta 2p= .09$ $t(25)= 0.90$, $p= .38$, $\eta 2p= .03$ $t(25)= 2.27$, $p= .03$, $\eta 2p= .17$	$F(2,22)= .745$, $p= .49$, $\eta 2p= .06$ $t(11)= 0.82$, $p= .21$ $t(11)= -1.14$, $p= .14$ $t(11)= -0.22$, $p= .41$	$F(2,46)= 1.3$, $p= .28$ $t(23)= 1.88$, $p= .074$ $t(23)= 0.021$, $p= .84$

Table 2

Explicit VSL Experimental Paradigm: Comparison of Results

-	Experiment 4	Turk-Browne et al. (2005) Experiment 1B
N Subjects	**24**	**8**
Familiarization sequence repetitions	equally split after 1st and 3rd positions	only after 3rd triplet position
Familiarization Accuracy (*SD*)	92.1 (*10.2*)	88.5 (*6.2*)
Test Accuracy: Attended	62%	77%
Attended Accuracy vs. chance (50%)	$t(23)= 3.03$ $p= .006$, $\eta 2p= .29$	$t(7)= 5.85$, $p= .001$, $\eta 2p= .83$
Test Accuracy: Unattended	54%	49%
Unattended Accuracy vs. chance (50%)	$t(23)= 2.10$ $p= .047$, $\eta 2p= .16$	$t(7)< 1$
Accuracy: Attended vs. Unattended	$t(23)= 1.59$, $p= .13$, $\eta 2p= .10$	$t(7)= 4.06$, $p= .005$, $\eta 2p= .70$
Attended Accuracy - Unattended Accuracy	7%	29%