The Impact of Attention on People’s Ability to Learn Two Statistical Patterns Simultaneously

by

Tess Allegra Forest

A thesis submitted in conformity with the requirements for the degree of Master of Arts
Graduate Department of Psychology
University of Toronto

© Copyright by Tess Allegra Forest 2017
The Impact of Attention on People's Ability to Learn Two Statistical Patterns Simultaneously

Tess Allegra Forest

Master of Arts

Graduate Department of Psychology
University of Toronto

2017

Abstract

While statistical learning has long been described as a learning mechanism that operates automatically across ages and modalities, there are a growing number of cases in which automatic learning is not observed, and in which attention seems to impact learning. In two experiments, we examined the role of instruction on adults' ability to learn two statistical patterns simultaneously. Results suggest that without explicit instruction to attend to either stream participants do not automatically learn both patterns. Moreover, results suggest that direct measures of learning (alternative force choice scores and explicit recall) are improved by instruction, while indirect measures (reaction time scores in a target detection task) are not impacted by instruction. This sets the foundation for future research to examine the effect that the development of attention has how children learn from their environment, as well as further our understanding of how automatic statistical learning actually is.
Acknowledgments

To Drs. Daphna Buchsbaum and Michael Mack - thank you for your helpful suggestions and support of this project.

To Johnny - thank you for helping me navigate our Master’s year with humor and patience.

To Anuya, Yaelan, Lexi, Andrew, Shelbie, Theresa, and the many other members of the Learning and Neural Development Lab, and the broader University of Toronto Psychology Department - thank you for your suggestions and encouragement along the way.

To my family and friends - thank you for the long-distance cheerleading and reminders to do things for fun sometimes, too.

And finally, to Dr. Amy Finn - an immense thank you for your enthusiasm, support, and care during this project. I am looking forward to the next 4 years of working together!
# Table of Contents

Acknowledgments........................................................................................................iii
Table of Contents........................................................................................................iv
List of Tables ................................................................................................................v
List of Figures ..............................................................................................................vi
List of Appendices .......................................................................................................vii

1  Introduction.............................................................................................................1
   1.1  Statistical Learning ......................................................................................... 1
   1.2  Complex Learning Environments ................................................................. 2
   1.3  Attention ......................................................................................................... 3
   1.4  Implicit and Explicit Statistical Learning ...................................................... 4
   1.5  Current Experiments ..................................................................................... 6

2  Experiment One .....................................................................................................6
   2.1  Methods ........................................................................................................ 6
      2.1.1  Participants ........................................................................................... 6
      2.1.2  Stimuli and Familiarization ................................................................. 6
      2.1.3  Tests ..................................................................................................... 7
      2.1.4  Scoring and Analyses .......................................................................10
   2.2  Results .......................................................................................................... 11
      2.2.1  Target Detection ..............................................................................11
      2.2.2  Alternative Force Choice .................................................................12
      2.2.3  Forced Recall ....................................................................................12
   2.3  Discussion ......................................................................................................13

3  Experiment Two ...................................................................................................14
   3.1  Methods .......................................................................................................14
      3.1.1  Participants .........................................................................................14
      3.1.2  Stimuli and Devices .........................................................................14
      3.1.3  Procedure ..........................................................................................14
      3.1.4  Analysis ..............................................................................................15
   3.2  Results ..........................................................................................................15
      3.2.1  Shape Instruction ............................................................................15
      3.2.2  Color Instruction ............................................................................17
      3.2.3  Dual Instruction ...............................................................................18
      3.2.4  All Instruction Groups ..................................................................20
      3.2.5  Correlations Between Dependent Measures ....................................22
   3.3  Discussion .....................................................................................................24

4  General Discussion .............................................................................................25

References ..................................................................................................................26

Appendix A ..............................................................................................................32
Appendix B ..............................................................................................................33
List of Tables

1. LMER Output table for Experiment One Target Detection Task
2. LMER Output table for Experiment Two Target Detection Task by Instructional Group
3. LMER Output table for Experiment Two across Instructional Group
4. LMER Output table for Position Restricted Analysis (Experiments One and Two)
List of Figures

1. Stimuli and Presentation
2. Target Detection, Alternative Force Choice, and Forced Recall Results, Experiment One
3. Target Detection, Alternative Force Choice, and Forced Recall Results, Experiment Two-Shape Instructional Group
4. Target Detection, Alternative Force Choice, and Forced Recall Results, Experiment Two-Color Instructional Group
5. Target Detection, Alternative Force Choice, and Forced Recall Results, Experiment Two-Dual Instructional Group
6. Target Detection, Alternative Force Choice, and Forced Recall Results, Experiment One and Two-All Instructional Groups
7. Correlation Matrixes between Dependent Measures, Experiments One and Two
8. Shape Binding Averages- All Instructional Groups
9. Color Binding Averages- All Instructional Groups
10. Nonword Binding Averages- All Instructional Groups
List of Appendices

1. Appendix A - Position Restricted Analyses for Target Detection Task, Experiments One and Two.

2. Appendix B - Results of Binding Tests, Experiments One and Two.
1 Introduction

1.1 Statistical Learning

Statistical learning has been described as an implicit learning process that allows us to make sense of the regularities in our world, in order to help learn about the structures we interact with in our daily lives (Aslin, Saffran, & Newport, 1998; Saffran et al., 1996). Implicit learning is defined as learning that occurs without conscious awareness of acquiring that knowledge; indeed, statistical learning often occurs without subjects being aware of the task they are completing (Amso & Davidow, 2012; Batterink, Reber, Neville, & Paller, 2015). Initially it was shown that 8-month old babies are able to use the statistical regularities, or patterns, available in an uninterrupted stream of nonsense speech to correctly learn where the boundaries of words are (Saffran et al., 1996). Since then, it has been demonstrated that newborn infants, babies, young and older adults are all able to use the transitional probabilities between items in a sequence to extract regular sequences (like words) in visual and auditory modalities. (Bulf, Johnson, & Valenza, 2011; Campbell, Zimerman, Healey, Lee, & Hasher, 2012; Teinonen, Fellman, Nääätäinen, Alku, & Huotilainen, 2009; Turk-Browne, Jungé, & Scholl, 2005). Statistical learning has also been shown to operate across species, in tamarind moneys and rats, emphasizing its broad availability as a learning mechanism. (Hauser, Newport, & Aslin, 2001; Toro & Trobalón, 2005).

Statistical learning’s broad availability is matched in its applicability to a wide variety of tasks. As mentioned, language has been one particularly clear application of statistical learning. Beyond extracting words from continuous unsegmented speech, it has also been shown that transitional probabilities can be used for tracking non-adjacent dependencies, or patterns that don’t only rely on items that are temporally next to each other, like word order or syntactic aspects of language acquisition (Aslin & Newport, 2012; Gomez, 2002; Thompson & Newport, 2007; Wonnacott, Newport, & Tanenhaus, 2008). Additionally, statistical learning can be leveraged to extract higher order categories, not just particular instances of items. For example, people can learn the patterns in the gist information in a series of images and the statistical patterns in the higher order information present in a series of scenes (Brady & Oliva, 2008; Finn, Lee, Kraus, & Hudson Kam, 2014; Fiser & Aslin, 2002; Marcus, Vijayan, Bandi Rao, & Vishton, 1999). While the vast applicability of statistical learning has been demonstrated
repeatedly, we know surprisingly little about the limitations of this learning mechanism, like how well it can account for learning in more complex learning environments or how it’s success relates to interaction with other cognitive processes (like attention, cf. Campbell et al., 2012; Toro, Sinnett, & Soto-Faraco, 2005; Turk-Browne et al., 2005). In order to further our understanding of how statistical learning functions, it is crucial that we begin to understand its boundaries.

1.2 Complex Learning Environments

Statistical learning is thought to operate automatically and implicitly, computing patterns in an environment even when the learner is unaware of it. If this mechanism is really operating continuously, we would expect very few situations in which people don’t learn the regularities in their environment, particularly in more complex environments. Surprisingly, there are a growing number of instances in which participants who are exposed to statistical patterns do not show learning of those patterns. For example, some work has studied the extent to which children can track the statistical patterns in a stream of artificial speech if there are multiple voices present during their exposure (Graf Estes & Lew-Williams, 2015). The authors exposed children to an artificial speech stream in which 8 different voices presented artificial speech. While they found that 8- and 10-month old infants were able to learn the regularities in the stream with 8 distinct voices, infants failed to learn these same patterns when only two voices were used. Separately, infants who were exposed to a stream of artificial speech made up of both two- and three-syllable nonce words were unable to successfully segment that stream of speech into words unless one of the included syllables was one they were previously familiar with (like ‘ma’) (Johnson & Tyler, 2010). This result is hard to reconcile with the idea that infants use the transitional probabilities in speech to learn where one word starts and another word ends, since the speech infants are exposed to in their daily lives includes words of a variety of syllable lengths. Another study showed that adults who are exposed to statistical patterns made up of sound groupings that are not possible in their native language fail to successfully learn the groupings of syllables in an auditory stream (Finn & Hudson Kam, 2008). Interestingly, adult participants who were exposed to two different auditory patterns failed to show learning of the second pattern unless they were presented with a clear cue to start tracking a new pattern, like a pause or voice change (Gebhart, Aslin, & Newport, 2009). These instances all raise questions about how automatic the use of
statistical learning is in our daily lives; if there are repeated cases in which participants fail to successfully segment speech in a controlled laboratory environment, how successfully can statistical learning explain learning in the more complex, real world learning environments? These examples illustrate that while statistical learning has been shown to be useful in tracking patterns, it’s limitations are not yet clearly understood.

1.3 Attention

To better understand how automatic statistical learning is, scientists have studied the extent to which attention is necessary or helpful. Multiple studies have suggested that attention is important for full mastery of patterns in statistical learning tasks. For instance, Toro et. al. (2005) showed that when participants were asked to complete an auditory statistical learning task they were less able to do so when there was a simultaneous task that used attentional resources in the same auditory stream, a different auditory stream, or an accompanying visual stream. They argued that when the attentional demands of a simultaneous task are high, people’s learning of statistical structures is negatively impacted. Another study, which looked at the impact of attention, used a set of two interleaved statistical streams with different colored shapes to ask whether paying attention to only one of the streams would impact peoples’ learning of the regularities in the other stream (Turk-Browne et al., 2005). They found that, indeed, participants only learned the patterns that had appeared in the color they attended to, using both direct and indirect measures of testing. Additionally, there is some indication that neural responses to attended as compared to unattended elements of a stream are fundamentally different (see Hasson, 2016). Collectively, these results suggest that attention might even be necessary for statistical learning.

This is hard to reconcile, however, given that pre-attentive infants and animals are able to use statistical learning (Saffran et al., 1996; Teinonen et al., 2009; Toro & Trobalón, 2005). For example, a study that looked at the extent to which statistical learning is implicit also found that direct measures of learning (like alternative force choice tests, and confidence judgements) are not necessarily correlated with indirect measures of learning (like reaction time measurements in a target detection task), which the authors suggested to mean that statistical learning proceed implicitly without explicit instructions on what to attend to (Batterink et al., 2015). Additionally, it was suggested that people who were completing a free-drawing task were still able to
successfully segment words from an auditory stream of an artificial language, despite having been told not to attend to the background noise during the drawing. This suggested that statistical learning was able to proceed normally even when participants’ attention was directed to something else (Saffran, Newport, Aslin, Tunick, & Barrueco, 1997).

Moreover, multiple studies have suggested that attention might even hinder people’s learning. For example, a replication of the Turk-Browne study described above found that older adults presented with the same paradigm showed equal learning of the stream they were attending to and the stream they were not attending to, suggesting that the older participant’s reduced cognitive control had led to an inability to successfully ignore the unattended stream leading to improved learning compared to younger adults (Campbell et al., 2012). Consequently, having allocated attention to only one part of their input actually impaired the younger adults from the original study (since they failed to automatically learn even the unattended material). While this cognitive control deficit might impair older adults on some working memory tasks or tasks that require explicit knowledge of items they are presented with, their lowered cognitive control might lead to advantages in tasks like statistical learning (Amer, Campbell, & Hasher, 2016; Thompson-Schill, Ramscar, & Chrysikou, 2009). Another indication that attention might not benefit people extracting regularities from their environment is that explicit instructions to attend to various aspects of an artificial language affected peoples’ likelihood of learning the patterns (Finn et al., 2014). Importantly, instructions to try to learn actually hurt peoples’ learning of categories within the artificial language.

Collectively, these mixed results on how attention influences pattern learning suggest that there may be some situations in which attention helps learning of statistical patterns, but others where deficits in attention might actually lead to better learning. Understanding more about the role of attention in statistical learning will help us understand how it interacts with other cognitive mechanisms to enable learning from our environment across the lifespan.

1.4 Implicit and Explicit Statistical Learning
Linked to the discussion about the extent to which attention helps or hinders statistical learning, is a question about whether the dependent measures used to study statistical learning are tapping into more implicit or explicit knowledge of the structure of the streams of information that participants have been exposed to. Importantly, the different ways of measuring statistical
learning can be either indirect, and measure more implicit knowledge of the stream, or direct, and measure more explicit knowledge of the patterns in someone’s environment. Batterink et. al. (2015) describe how using different dependent measures might tap into different types of knowledge of the structure of someone’s input (Ryan, 2017). For example, using measures of reaction time in a target detection task will indirectly measure implicit knowledge of a statistical pattern. In this task, participants are asked to press every time they see or hear a certain element of the pattern, and learning is measured by calculating the difference in reaction times to unpredictable and predictable elements of the input pattern, with second and third items in a sequence being more predictable than the first item (which is not at all predictable). This more indirect measure is thought to capture implicit knowledge of the stream because participants do not need to be aware of their own knowledge of stream structure to show faster reaction times to predictable elements of a pattern, and has been used to show that participants extract structure from a stream within only a few presentations of the elements in the pattern (Batterink, 2017). Conversely, more direct measures of learning like two alternative force choice tests, confidence judgements, or forced recall of a pattern tap into participants’ explicit knowledge of the structure of their input, since it is generally thought that to perform well on these measures participants need to have some awareness of their knowledge. Others have gone as far as to suggest that statistical learning is better characterized as a set of memory processes, and that explicit computation of statistics is not needed to model the type of learning reported, emphasizing the importance of carefully distinguishing what it is that each measure of learning is reflecting (Thiessen, 2017). Importantly, it is possible that statistical learning could lead to either implicit or explicit representations of patterns in our environment or both, but that these forms of knowledge may not be directly related in any given task or participant. For example, someone could have implicit knowledge of a stream’s structure and show no knowledge of this on a test that requires explicit knowledge to perform well on. Indeed, our ability to learn statistics in our environment and our ability to then use those statistics are not necessarily the same (see Hasson, 2016). This could mean that while participants have some implicit knowledge of a structure, they do not have the explicit knowledge they might need to perform well on alternative force choice tests. Teasing apart the different contributions of implicit and explicit knowledge to our representations of patterns in our environments will again help us understand how other cognitive resources might impact one or both of these sources of knowledge.
1.5 Current Experiments

Given the possible contributions of both implicit and explicit knowledge to statistical learning, understanding how attention mediates learning, especially in complex learning environments, will help us make sense of the differing findings regarding the role of attention in statistical learning, as well as better understand how this learning mechanism works in the brain. To further understand how well statistical learning can account for learning in more complex environments, we created a visual statistical learning paradigm in which participants were exposed to two visual patterns simultaneously. In order to answer questions about the extent to which attention impacts implicit and explicit knowledge of statistical structure, we then manipulated participants’ instructions to conduct a series of studies which asked the questions 1) Can people learn two unrelated statistical patterns simultaneously, 2) Does explicit instruction to attend to one stream or the other improve learning for either stream, and 3) Are implicit and explicit knowledge of stream structure differentially impacted by instruction?

2 Experiment One

2.1 Methods

2.1.1 Participants

30 undergraduate students from the University of Toronto participated in exchange for course credit (Mean Age = 18.84 years, 69% female).

2.1.2 Stimuli and Familiarization

All stimuli appeared on an Apple desktop computer screen, and were presented using PsychoPy (Peirce, 2009). Stimuli displays consisted of two streams of visual objects. The first stream was made up of 9, 5x5cm colored squares, which appeared in 3 predictable triplets, so that the transitional probability within a triplet was 1.0, and the transitional probability between triplets was 0.33. The second stream consisted of 9 squares filled with distinct shapes. These shapes were also divided into three triplets. One shape appeared in the center of each colored square, as illustrated in Figure 1. The streams were correlated such that each object in one stream could
appear in tandem with three colors from the second stream, and vice versa. For example, the green square might appear with three shapes, and the shape shown on the green square might have appeared with the three colors. Consequently, while there was a correlation between the two streams; one color was not uniquely associated with only one shape. Participants watched a 7-minute sequence of overlaid squares, in which triplets from each stream were offset so that the dip in transitional probability which signaled a triplet boundary in one pattern did not correspond with the transitional probability dip in the other pattern (the first item in a shape-triplet occurred with the second item in a color-triplet (see Figure 1a)). In each stream, the order of the triplets was randomly generated per participant, with the condition that one triplet could not directly follow an instance of the same triplet. All triplets appeared an equal number of times. Each image was presented for 600ms with an ISI of 200ms.

Figure 1. A) Example stimuli for Experiment One (clockwise from top left: color stream, shape stream, overlaid color and shape stream as presented in experiment) B) Illustration of the stream with offset dips in Transitional Probability between Color and Shape Streams.

2.1.3 Tests
Participants completed three types of tests to assess their knowledge of the structure in each stream. The first was a target detection task (see Batterink et al., 2015; Kim, Seitz, Feenstra, & Shams, 2009) in which participants saw a continuation of the streams presented during training,
but were asked to detect a particular target (a given color or shape) by pressing a button as quickly as possible each time they saw that target (e.g. a red square). Each color and shape served as a target during one detection stream that was 27 items long and included three instances of the given target (resulting in a total of 54 target detections for each participant). There were 2 counterbalanced versions of the order in which the detection streams were presented. For each detection, reaction time from the onset of the image to participants’ button press was recorded. Then, reaction times for each position in a triplet were averaged and compared individually for each stream.

Next, participants completed a series of two-alternative force choice tests. They were asked to choose which of two sequences seemed more familiar to them. In all cases, they were asked to choose between a triplet that was present during exposure and various foils which are detailed below. In total, there were 69 test items, made up of 6 types of alternative force choice tests. Three of these test types allowed us to determine what participants learned about each stream independently. One of these (Color Test) tested learning of the color stream, by comparing triplets from the color stream to sequences of three colors that were not a reliable triplet during familiarization (but remained in the same triplet position they had appeared in during familiarization). The shapes that appeared with each choice were a previously seen triplet, and the same shape triplet was paired with each choice. Participants completed 12 color tests. The second type of test (Shape Test) compared triplets from the shape stream to sequences of three shapes that were not a reliable triplet during familiarization (the 12 test items were randomly selected by participant from a bank of all possible test items, which included position-matched foils, as well as foils where two of the items had previously appeared together but the third was either a first-position or third-position item from a different triplet). Here the colors were held constant between choices, and were a previously seen color triplet. Participants completes 12 shape tests (selected in the same way as Color Test foils). The third type of test (Preference Test) asked participants to choose between a correct color triplet (paired with an incorrect shape triplet) and a correct shape triplet (paired with an incorrect color triplet). Participants completed 9 preference tests. This allowed us to address whether participants showed a preference for one stream over the other.

The following three types of AFC-test were designed to help us understand whether participants were tracking the features or whole objects in their input, by asking people to choose
between features (shapes and colors) that appeared together (correctly bound, whole images) and features that didn’t appear together (unbound) in their input. The results appear in Appendix B. The first of these tests (Binding Triplet Test) asked participants to choose between a correct color triplet paired with a correct shape triplet in a binding that had not been possible during the familiarization phase, and the same correct color triplet paired with a set of shapes that could have appeared with those colors during familiarization but wasn’t a coherent shape triplet. (There was also an equivalent set of test items which held the shape triplets constant, and used correctly paired and incorrectly paired colors as the distinguishing element between the two choices). Participants completed 12 binding triplet tests. This allowed us to address whether participants preferred the sequence which matched the whole objects they could have seen during familiarization to the sequences which retained the triplet structure of each of the features. The second of these tests (Binding Non-triplets) asked participants to choose between a set of three squares whose features could have appeared together during familiarization and a set of squares whose features couldn’t have appeared together during familiarization. None of the sequences were allowable triplets in either stream. This allowed us to address whether people had a preference for objects whose features could have appeared together during familiarization over features which never appeared together, and allowed us to examine if people learned which bindings are allowable or focused on the streams’ features independently. Participants completed 12 binding non-triplet tests. One final test (singleton tests) presented participants with individual squares rather than triplets- one choice consisted of a correctly paired color and shape, while the other choice was made up of an incorrectly paired combination. Participants completed 12 singleton tests.

For each of these tests, one set of objects was presented in succession on the one side of the screen and then disappeared, followed by the second set of objects on the other side. Starting side was randomized between trials. Participants pressed one button to indicate they thought the first set of objects seemed more familiar and a different button to indicate they thought the second set of objects seemed more familiar. The color test, shape test, and two binding tests appeared first, in a randomized order. The preference tests appeared next, after the other triplet tests, to avoid any learning of incorrect structures that could have occur during these tests. Finally, the singleton tests appeared. These were completed last to avoid drawing participants’ attention to the relationship between individual shapes and colors.
After completing the 2AFC tests, all participants were asked to write down the pattern that the colors they saw had appeared in, and, separately, the order the shapes had appeared in. Participants were provided a paper form to complete, which included a printed bank of all the shape images they had seen and the written the names of the colors they had seen during the exposure and test phases.

2.1.4 Scoring and Analyses

All reaction times less than 100ms or greater than 700ms were excluded. Then the median reaction time for each participant was calculated for each position in the color stream and each position in the shape stream. A by-participant, by-position, by-stream standard deviation was then calculated, and any reaction times which then fell above or below two standard deviations from each participants median RT for that position color or shape were excluded. Across all participants, this left 790 trials in the for the color stream and 778 trials for the shape stream. First, reaction times for position one, two, and three items were compared in an ANOVA (and using pair-wise comparisons where warranted). Then, given the repeated measures nature of this design, a follow up analysis was conducted using linear mixed effects modeling (using the LMER package in R). All detections were then scored according to the position in the task at which a particular shape or color was the target (1-18, “position in task”), how close to the beginning of that target’s detection stream the detection was (1-28, “position in stream”), and which of 3 detections of each target that detection was (1-3, “detection number”). These variables were then used in a linear mixed effects model to analyse the effect of triplet position (first, second, or third in a triplet) on reaction time. The model structure used included fixed effects for position in task, position in stream, and detection number, as well as the interaction between triplet position and position in task, and triplet position and detection number. Random, by-participant slopes were included for all fixed effects with a conditional growth model covariance structure. All models were run separately for shape and color stream targets, and used the LMER package in R.

The alternative force choice data were analyzed by scoring participants responses (out of 1) based on whether they correctly chose the previously present triplet. Their responses were then averaged for a by-participant accuracy score on each test type. These scores were then
averaged to compare group means to different test types (ex: color learning vs. shape learning) and to chance.

Explicit knowledge judgements were coded as the number of correct within-triplet transitions a participant wrote down (maximum correct = 6). This was calculated separately for color and shape streams.

Additionally, correlations between all dependent measures of each stream were calculated. First, learning scores were calculated for each participant on the target detection task by subtracting their third position median RT from their first position median RT, separately for color and shape stream reaction times. Positive values on this indicate the predicted decrease in reaction time from first position items to third position items, while negative values indicate the opposite. These were then used to calculate correlations with the other by-participant scores on each dependent variable.

2.2 Results

2.2.1 Target Detection

Reaction time analyses for the shape stream revealed faster reaction times for later position shapes ($F(1,88) = 2.66, p = .11, n_p^2 = .03$). Pairwise comparisons showed a significant difference between reaction times for shapes in position one to two ($t = 1.93, df = 443.47, p = 0.05$), and from position one to three ($t = 3.65, df = 443.17, p < 0.001$), but not from position two to three ($t = 1.51, df = 480, p = 0.13$). Overall, reaction times for color targets did not decrease with triplet position ($F(1,88) = 2.37, p = .127, n_p^2 = .03$), although pairwise comparisons showed that position three reaction times were slower than position one ($t = -3.20, df = 371.02, p < 0.01$), in the opposite direction of what one would expect if the triplets were learned.

In line with the analyses above, a linear mixed effects model with random by-participant slopes and intercepts for triplet positions, position in detection stream, and position in task showed a significant effect of triplet position during shape detection, with faster reaction times to shapes that had appeared in later positions in triplets ($\beta = -2.377e-02, t = -2.406, Figure 2a, Table 1$). The equivalent model for color detection showed the opposite result, with reaction times to later position colors being significantly slower than to earlier position shapes ($\beta = 1.392e-02, t = 2.008, Figure 2c, Table One$). There were no significant interactions between the number of detections participants had made for a given target (‘detection’, 1-3) and the position of the
target in the triplet, or the trial number (‘position in task’) and the position in the triplet for either the shape or color streams.

Table 1.
LMER Results for Shape and Color stream Target Detection Task

<table>
<thead>
<tr>
<th>Effect</th>
<th>Shape Stream Learning</th>
<th></th>
<th></th>
<th>Color Stream Learning</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Est.</td>
<td>SE</td>
<td>t</td>
<td>Est.</td>
<td>SE</td>
<td>t</td>
</tr>
<tr>
<td>(Intercept)</td>
<td>4.702e-01</td>
<td>2.112e-02</td>
<td>22.265***</td>
<td>3.926e-01</td>
<td>1.668e-02</td>
<td>23.542***</td>
</tr>
<tr>
<td>Detection</td>
<td>-4.700e-03</td>
<td>7.094e-03</td>
<td>-0.663</td>
<td>6.441e-03</td>
<td>5.320e-03</td>
<td>1.211</td>
</tr>
<tr>
<td>Triplet Pos.</td>
<td>-2.377e-02</td>
<td>9.877e-03</td>
<td>-2.406*</td>
<td>1.392e-02</td>
<td>6.931e-03</td>
<td>2.008*</td>
</tr>
<tr>
<td>Pos. in Task</td>
<td>2.146e-04</td>
<td>1.573e-03</td>
<td>1.573e-03</td>
<td>-5.772e-04</td>
<td>9.857e-04</td>
<td>-0.586</td>
</tr>
<tr>
<td>Detection: Triplet Pos.</td>
<td>1.573e-03</td>
<td>1.573e-03</td>
<td>1.532</td>
<td>-3.774e-03</td>
<td>2.455e-03</td>
<td>-1.538</td>
</tr>
<tr>
<td>Triplet Pos.: Pos. in Task</td>
<td>-1.799e-05</td>
<td>-1.799e-05</td>
<td>-0.025</td>
<td>3.283e-04</td>
<td>4.005e-04</td>
<td>0.820</td>
</tr>
</tbody>
</table>

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1

2.2.2 Alternative Force Choice

On alternative force choice tests, participants showed learning of the shape stream (56% correct) ($t = 2.17$, $df = 343$, $p < 0.05$, $d = 0.12$, Figure 2b), although they did not show learning of the color stream (51% correct) that was significantly different from chance ($t = 0.27$, $df = 344$, $p = 0.79$, $d = 0.01$, Figure 2d). Accordingly, participants showed a slight preference for shape over color triplets ($t = -2.08$, $df = 239$, $p = 0.04$, $d = 0.13$).

2.2.3 Forced Recall

Explicit Knowledge judgements also showed no ability to recall the shape ($mean$ transitions $= 0.4$ (out of 6 possible), $SD = 0.82$ (Figure 2b) or color patterns ($mean = 0.87$, $SD = 0.9$) (Figure 2c), although there was a trend toward better explicit recall of the color stream, as compared to the shape stream ($t = -1.956$, $df = 57.47$, $p = 0.06$, $d = 0.50$).
These results suggest that without explicit instruction to attend to one stream over the other, participants were unable to learn both statistical streams. This is certainly the case for the color stream in which there is no learning on any of the direct (alternative forced choice or forced recall) or indirect (target detection) measures. However, participants display learning of the shapes, in both the target detection task and 2AFC test. It appears, therefore, that participants do not learn both streams when they are not made aware of the presence of both (or told to search for anything in particular) prior to exposure.

Finally, the lack of relationship between the target detection and the alternative force choice or explicit recall measures of the shape stream indicates that the dependent variables are likely representing different forms of knowledge. The correlation between the alternative force choice measure and the reaction time measure of the color could suggest that both of these tests are tapping into the same source of knowledge, but chance performance on these measures limits the conclusions that can be drawn from this correlation.
Together, the results from Experiment One suggest that statistical learning is not able to automatically account for learning two, unrelated, statistical patterns simultaneously. This lays the groundwork for Experiment Two, which asks whether explicit instruction to one stream boosts learning for one or both of the statistical streams.

3 Experiment Two
In Experiment Two we were interested in understanding the extent to which attention is necessary for successful statistical learning in a complex environment. Namely, we were interested in whether instructing people to attend to one or both of two statistical streams will differentially affect learning on any of our dependent measures.

3.1 Methods
3.1.1 Participants
90 adults (across 3 conditions, 30 per condition, Mean age = 19.49 years, 73% female) participated in this experiment. Recruitment and compensation procedures matched those in Experiment 1.

3.1.2 Stimuli and Devices
All stimuli and devices were the same as in Experiment 1 except minor modifications to the instructions that are described below.

3.1.3 Procedure
3.1.3.1 Familiarization
All participants were told there was an order governing the items that they were about to see and that they should please try to learn it. Thirty were told that the shapes occurred in a particular order (shape instruction), 30 were told that the colors occurred in a particular order (color instruction) and the remaining 30 participants were told that both the shapes and colors occurred in particular order and to learn both (dual instruction).
3.1.3.2 Test Phase
Participants completed the same tests as participants in Experiment 1.

3.1.4 Analysis
Analyses were the same as described in Experiment one with the addition scores were also compared to the other instructional conditions, and instructional condition and the interaction between instructional condition and triplet position were included as fixed effects in LMER models for the target detection task. Additionally, models with the same structure as the model from Experiment 1 were run separately for each instructional condition.

3.2 Results
3.2.1 Shape Instruction
3.2.1.1 Target Detection
Reaction times for participants in the shape instruction condition did not differ by triplet positions for shapes ($F(1,85) = 1.28, p = .26, \eta_p^2 = .01$) or colors ($F(1,85) = 0.00, p = .98, \eta_p^2 < .01$). The LMER results for the model run with only participants who received instruction to learn the shape stream also showed a significant effect of triplet position on reaction times for the shape stream ($\beta = -3.932 \times 10^{-2}, t = -2.842, Figure 3a, Table Two$). The equivalent model for the color stream showed no effect of triplet position on reaction time ($\beta = 6.745 \times 10^{-3}, t = 0.853, Figure 3c, Table Two$).
Instructed to learn the shape pattern showed a significant preference for shape triplets over color different than chance ($t = 6.97, df = 347, p < 0.0001, d = 0.37, \text{Figure 3b}$) and significantly different than their performance on the color stream ($t = 2.75, df = 685.75, p < 0.01, d = 0.21$). Their performance on the color stream was not significantly different than chance ($t = 1.49, df = 330, p = 0.138, d = 0.15, \text{Figure 3d}$). Participants who were instructed to learn the shape pattern showed a significant preference for shape triplets over color triplets ($t = -5.31, df = 239, p < 0.00001, d = 0.34$).

### Table Two.
LMER Results for Shape and Color Stream Target Detection Task, for Shape, Color, and Dual Instructional Condition.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Shape Stream Learning</th>
<th>Color Stream Learning</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Est.</td>
<td>SE</td>
</tr>
<tr>
<td><strong>Shape Instructions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Intercept)</td>
<td>4.936e-01</td>
<td>2.718e-02</td>
</tr>
<tr>
<td>Detection</td>
<td>-1.182e-02</td>
<td>9.509e-03</td>
</tr>
<tr>
<td>Triplet Pos.</td>
<td>-3.932e-02</td>
<td>1.384e-02</td>
</tr>
<tr>
<td>Pos. in Task</td>
<td>-8.889e-04</td>
<td>2.141e-03</td>
</tr>
<tr>
<td>Detection : Triplet Pos.</td>
<td>5.742e-03</td>
<td>4.579e-03</td>
</tr>
<tr>
<td><strong>Color Instructions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Intercept)</td>
<td>4.853e-01</td>
<td>2.240e-02</td>
</tr>
<tr>
<td>Detection</td>
<td>-4.135e-03</td>
<td>7.981e-03</td>
</tr>
<tr>
<td>Triplet Pos.</td>
<td>-3.189e-02</td>
<td>1.070e-02</td>
</tr>
<tr>
<td>Pos. in Task</td>
<td>-6.832e-04</td>
<td>1.794e-03</td>
</tr>
<tr>
<td>Detection : Triplet Pos.</td>
<td>4.292e-03</td>
<td>3.772e-03</td>
</tr>
<tr>
<td><strong>Dual Instructions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Intercept)</td>
<td>4.343e-01</td>
<td>2.580e-02</td>
</tr>
<tr>
<td>Detection</td>
<td>-6.061e-03</td>
<td>9.014e-03</td>
</tr>
<tr>
<td>Triplet Pos.</td>
<td>-1.726e-03</td>
<td>1.245e-02</td>
</tr>
<tr>
<td>Pos. in Task</td>
<td>1.677e-03</td>
<td>2.115e-03</td>
</tr>
<tr>
<td>Detection : Triplet Pos.</td>
<td>3.572e-03</td>
<td>4.138e-03</td>
</tr>
</tbody>
</table>

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1

#### 3.2.1.2 Alternative Force Choice

Participants who were instructed to learn the pattern in the shape stream showed learning of the shape stream that was significantly different than chance ($t = 6.97, df = 347, p < 0.0001, d = 0.37, \text{Figure 3b}$) and significantly different than their performance on the color stream ($t = 2.75, df = 685.75, p < 0.01, d = 0.21$). Their performance on the color stream was not significantly different than chance ($t = 1.49, df = 330, p = 0.138, d = 0.15, \text{Figure 3d}$). Participants who were instructed to learn the shape pattern showed a significant preference for shape triplets over color triplets ($t = -5.31, df = 239, p < 0.00001, d = 0.34$).
3.2.1.3 Forced Recall

Participants who were asked to learn the shape pattern recalled significantly more shape transitions than color transitions ($t = -2.94$, $df = 35.99$, $p < 0.01$, $d = 0.76$, Figure 4b/d).

3.2.2 Color Instruction

3.2.2.1 Target Detection

Reaction times for participants who received color instruction did not differ overall based on triplet position for either shape targets ($F(1,79) = 0.19$, $p = .67$, $n^2_p < .01$) or color targets ($F(1,79) = 0.32$, $p = .58$, $n^2_p < .01$). LMER results showed significant decrease in reaction time across triplet position for shape targets ($\beta = -3.189e-02, t = -2.98, Figure 4a, Table Two$). The equivalent model for color targets showed no significant effect of triplet position ($\beta = 7.921e-03, t = 0.42, Figure 4c, Table Two$).
3.2.2.2 Alternative Force Choice
Performance by participants in this condition on shape items was better than chance \((t= 1.95, df= 341, p= 0.05, d = 0.11, Figure 4b)\). Performance on color items was significantly greater than chance \((t= 7.72, df= 346, p< 0.0001, d = 0.41, Figure 4d)\), and significantly better than shape items \((t= -3.80, df= 681.69, p< 0.001, d = 0.29)\). As anticipated, this group also showed a significant preference for color triplets \((t= 4.86, df = 239, p< 0.00001, d = 0.31)\).

3.2.2.3 Forced Recall
Participants produced more correct color transitions than shape transitions \((t= -5.12, df= 35.10, p< 0.0001, d = 1.32, Figure 4d)\).

![Figure 4. Results of Indirect and Direct measures of learning on shape and color streams for subjects with COLOR INSTRUCTION: a) Indirect measure of shape learning, b) direct measures of shape learning (Alternative Force Choice, and Explicit Recall), c) indirect measure of color learning, d) direct measures of color learning (Alternative Force Choice, and Explicit Recall). Error bars represent Standard Error of the Mean.](image)

3.2.3 Dual Instruction
3.2.3.1 Target Detection
Reaction times for participants who received instruction to learn both streams also showed no significant decreases in reaction time across triplet positions in the shape stream \((F(1,80) = \ldots)\).
0.52, \( p = .47, n_p^2 = .01 \), or the color stream (\( F(1,80) = 0.42, p = .52, n_p^2 = .01 \)). LMER models for this condition revealed no significant effects of triplet position for either shape or color targets (Shape: \( \beta = -1.726\times10^{-3}, t = -0.14, \text{Table Two, Figure 5a} \). Color: \( \beta = 7.692\times10^{-3}, t = 0.85, \text{Table Two, Figure 5c} \)).

### 3.2.3.2 Alternative Force Choice

Performance was better than chance for shape (\( t = 4.90, df = 343, p < 0.00001, d = 0.26, \text{Figure 5b} \)) and color (\( t = 6.10, df = 345, p < 0.00001, d = 0.33, \text{Figure 5d} \)) test items. They showed no preference for color or shape stream (\( t = 0.39, df = 239, p = 0.70, d = 0.02 \)), and their performance on shape and color streams was not significantly different (\( t = -0.77, df = 687.63, p = 0.44, d = 0.06 \)).

### 3.2.3.3 Forced Recall

Participants who received instructions to learn both the color and shape patterns recalled significantly more correct color transitions than shape transitions (\( t = -5.29, df = 35.48, p < 0.00001, d = 1.37, \text{Figure 5} \)).

![Figure 5. Results of Indirect and Direct measures of learning on shape and color streams for subjects with DUAL INSTRUCTION: a) Indirect measure of shape learning, b) direct measures of shape learning (Alternative Force Choice, and Explicit Recall), c) indirect measure of color learning, d) direct measures of color learning (Alternative Force Choice, and Explicit Recall). Error bars represent Standard Error of the Mean.](image-url)
3.2.4 All Instruction Groups

3.2.4.1 Target Detection

The LMER model which included instructional condition as a fixed effect (Table Three) showed a significant effect of triplet position for shapes ($\beta=-2.419e-02$, $t=-3.39$, Figure 6a). The equivalent model for color targets, showed no main effect of triplet position ($\beta=7.611e-03$, $t=1.46$, Figure 6c), although there was an effect of the number of detections for a given target, such that the second and third times participants detected the same target, they got progressively slower ($\beta=9.158e-03$, $t=2.46$). Additionally, there was a significant interaction between detection and triplet position ($\beta=-3.833e-03$, $t=-2.20$).

Table Three.
LMER Results for Shape and Color Stream Target Detection Task, across conditions.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Estimate</th>
<th>SE</th>
<th>t</th>
<th>Estimate</th>
<th>SE</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>(Intercept)</em></td>
<td>4.711e-01</td>
<td>1.468e-02</td>
<td>32.096***</td>
<td>3.863e-01</td>
<td>1.227e-02</td>
<td>31.488***</td>
</tr>
<tr>
<td>Detection</td>
<td>-7.385e-03</td>
<td>5.105e-03</td>
<td>-1.447</td>
<td>9.158e-03</td>
<td>3.724e-03</td>
<td>2.459*</td>
</tr>
<tr>
<td><strong>Triplet Pos.</strong></td>
<td>-2.419e-02</td>
<td>7.144e-03</td>
<td>-3.386***</td>
<td>7.611e-03</td>
<td>5.223e-03</td>
<td>1.457</td>
</tr>
<tr>
<td>Pos. in Task</td>
<td>4.084e-05</td>
<td>1.179e-03</td>
<td>0.035</td>
<td>8.524e-04</td>
<td>6.969e-04</td>
<td>1.223</td>
</tr>
<tr>
<td>Condition</td>
<td>-6.773e-03</td>
<td>6.755e-03</td>
<td>-1.003</td>
<td>-1.398e-02</td>
<td>8.642e-03</td>
<td>-1.617</td>
</tr>
<tr>
<td>Triplet Pos. : Condition</td>
<td>4.511e-03</td>
<td>3.476e-03</td>
<td>1.298</td>
<td>2.593e-03</td>
<td>3.061e-03</td>
<td>0.847</td>
</tr>
<tr>
<td><strong>Detection : Triplet Pos.</strong></td>
<td>4.510e-03</td>
<td>2.438e-03</td>
<td>1.850</td>
<td>-3.833e-03</td>
<td>1.742e-03</td>
<td>-2.201*</td>
</tr>
<tr>
<td>Triplet Pos. : Pos. in Task</td>
<td>5.621e-04</td>
<td>4.981e-04</td>
<td>1.128</td>
<td>-1.870e-05</td>
<td>2.961e-04</td>
<td>-0.063</td>
</tr>
</tbody>
</table>

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 .’ 0.1

3.2.4.2 Alternative Force Choice

Participants who received instruction to learn the shape pattern showed better learning of the shape pattern than participants in the color instruction group ($t = -3.33$, $df = 683.91$, $d = 0.25$, $p < 0.001$) and the no-instruction group ($t = 3.19$, $df = 686.61$, $p < 0.01$, $d = 0.24$, Figure 6b). Their color performance didn’t differ from the no instruction group ($t = 1.77$, $df = 685.98$, $p = 0.08$, $d = 0.13$, Figure 6d). Participants who received instruction to learn the color pattern showed better learning of the color pattern than participants who received instruction to learn the shape pattern ($t = 3.21$, $df = 683.65$, $p < 0.01$, $d = 0.24$) or who didn’t receive any instructions ($t = 5.03$, $df = 683.91$).
685.06, \( p < 0.000001, d = 0.38, \text{Figure 6d} \). Their performance on the shape stream did not differ from the no-instruction group \((t = -0.14, df = 683.97, p = 0.88, d = 0.01, \text{Figure 6b})\). In participants who received instruction to learn both patterns, performance on the color items was not significantly different from color-item performance in participants who received color instruction \((t= 0.10, df= 690.33, p= 0.32, d= 0.08, \text{Figure 6d})\); likewise, shape performance did not differ from participants who had received shape instruction \((t= 1.31, df= 688.71, p= 0.19, d = 0.10, \text{Figure 6b})\).

### 3.2.4.3 Forced Recall

Participants who received instructions to learn the shape stream did not recall more correct shape transitions \((t = -1.19, df = 43.93, p = 0.24, d = 0.31, \text{Figure 6b})\) or color transitions \((t = -0.24, df = 53.12, p = 0.81, d = 0.06, \text{Figure 6d})\) than participants from Experiment One who received no explicit instruction. Participants who received instructions to learn the color stream recalled significantly more color transitions than participants who were asked to learn the shape pattern \((t= 4.01, df= 43.19, p< 0.001, d= 1.05, \text{Figure 6d})\), and participants from Experiment One who were not explicitly asked to learn either pattern \((t= 4.31, df= 36.84, p< 0.001, d = 1.15, \text{Figure 6d})\). Their performance was not different from participants who were asked to learn both the color and the shape patterns on the shape \((t = 0.74, df = 57.85, p = 0.46, d = 0.19, \text{Figure 6b})\) or color stream \((t = 0.43, df = 57.61, p = 0.67, d = 0.11, \text{Figure 6d})\). Their shape transition recall was not significantly better than that of participants in Experiment one \((t = 0.34, df = 56.21, p = 0.73, d = 0.26, \text{Figure 6b})\).
Figure 6. Learning in all conditions for all dependent measures, Experiments One and Two: a) Indirect measure of shape learning, b) direct measures of shape learning (Alternative Force Choice, and Explicit Recall), c) indirect measure of color learning, d) direct measures of color learning (Alternative Force Choice, and Explicit Recall). Error bars represent Standard Error of the Mean.

3.2.5 Correlations Between Dependent Measures

3.2.5.1 No Instruction

Correlations between dependent measures revealed that no dependent measures for the shape stream were related (all p’s >0.4, Figure 7). For the color stream, however, 2AFC and target detection scores were significantly related \( (\rho = 0.55, S = 2036.8, p < 0.01) \), such that participants who performed better on AFC tests showed less of a decrease in reaction time from position one to position three colors. No other dependent measures of the color stream were significantly correlated.

3.2.5.2 Shape Instruction

In the shape-instruction condition, performance on the alternative force choice tests for shapes and explicit recall of shapes were significantly negatively correlated \( (\rho = -0.59, S = 6459.1, p < 0.001, \text{Figure 7}) \). No other measures of shape stream knowledge were related. These participants scores on alternative force choice tests for color and target detection scores for color were also
significantly correlated ($rho = 0.53, S = 1902.6, p< 0.01$). No other dependent measures of color were related.

### 3.2.5.3 Color Instruction

Participants who received instruction to learn the color stream showed a significant correlation between their shape target detection score and the number of correct shape transitions recalled ($rho= 0.45, S = 1789.4, p< 0.05$), and no other significant correlations on dependent measures of shape stream learning. For color measures, participants who received instructions to learn the color pattern showed a significant correlation between their alternative force choice scores and forced recall scores ($rho= 0.41, S = 1937.7, p< 0.05$). They also showed a significant correlation between their reaction time scores and their alternative force choice scores ($rho = 0.86, S = 458.4, p< 0.00001$).

### 3.2.5.4 Dual Instruction

Participants who received instruction to learn both the color and shape streams showed a significant correlation in their shape target detection scores and the number of shape transitions recalled ($rho= 0.45, S = 2478.6, p< 0.05$). No other measures of shape stream learning were correlated. These participants also showed a correlation between their target detection for color learning and their alternative force choice scores ($rho= 0.75, S = 1129, p< 0.00001$), as well as the number of color transitions they recalled ($rho= 0.42, S = 2594.7, p<0.05$).
Discussion

Overall, results from Experiment Two suggest that with explicit instruction to attend to one stream, participants show knowledge of that stream on the 2AFC tests, regardless of what that stream is. Given that 2AFC performance has been correlated with confidence judgements, this is likely representing more explicit knowledge than the target detection task (Batterink et al., 2015). This supports the idea that attention benefits statistical learning. This is additionally supported by the increase in correctly recalled transitions on the forced recall test for the cued stream. It is interesting to note that although 2AFC performance improved, performance on the

![Figure 7. Correlations between all dependent measures of shape and color stream knowledge for Experiments One and Two.](image)
indirect measure—target detection—did not. Insofar as indirect measures are a better representation of implicit memory and 2AFC, a more direct measure of explicit memory, this suggests that attention to a particular stream only impacts the more explicit or direct expression of that knowledge.

The second important finding from Experiment Two is that instructions to attend to one stream do not automatically improve learning of the patterns in the other stream. While it is possible that awareness of any structure in the input would have improved participants’ knowledge of all statistical information (both streams), this was not the case. Participants who received instructions to learn the shape stream improved on direct measures of the shape stream only, and participants who received instructions to learn the color stream improved their performance on color test items and showed no additional benefit on measures reflecting knowledge of the shape stream (which matched the baseline performance of shape knowledge from Experiment One).

Importantly, participants who received instructions to learn both streams showed learning of both on the 2AFC measures. This shows that it is possible to learn both even though they are not both learned automatically in the no instruction condition. Interestingly, indirect learning was not shown for either stream in this condition. This could mean that the underlying representation of shape and color stream knowledge was solely explicit when participants were asked to complete an arguably harder learning task than in conditions where they only received one set of instructions.

The correlations between dependent measures in Experiment Two also speak to the nuanced differences in the shape and color streams’ status to the learner. Unlike in Experiment One, the correlations between dependent measures reflect that there may be some correlation between the direct and indirect measures used. While measures of color learning were consistently correlated, this was less true on measures of shape stream learning. As with Experiment One, the conclusions that can be drawn from the correlations of dependent measures of color are limited for the shape instruction group especially, given the weak color learning in these participants. The correlation between the alternative force choice scores and forced recall scores for participants who received color instructions reinforces the notion that participants’ performance on the 2AFC measure is more explicit than implicit and so the boost in learning could be via more explicit learning mechanisms that are not traditionally thought of in explaining
statistical learning phenomena (c.f., Shohamy & Turk-Browne, 2013). However, the relationship between explicit recall and 2AFC performance was not strong (or even positive) in the shape-instruction group on measures of shape-learning. The difference in results between the measures of shape and color again indicate that shape, unlike color, might be learned more automatically than color as mentioned in the discussion section of Experiment One. Color, on the other hand seems to have only been learned explicitly, and only when instruction was given to learn the color stream.

4 General Discussion

Across two experiments, our results suggest that attention to a stream of statistical information improves learning of the attended information as expressed in more direct measures of learning (2AFC and explicit recall) but not in more indirect measures of learning (target detection). These results add to a growing body of literature on the usefulness of attention for statistical learning, and speak to the importance of understanding the differences in the implicit and explicit representations of statistical knowledge, as measured by indirect and direct measures respectively. While the role of attention in statistical learning has been explored previously, it was still unknown how it would impact learning of multiple structures simultaneously, something that is more naturalistic when thinking about humans parsing their environments in the real world. Moreover, all of the previous work looking at the impact of attention on statistical learning used 2AFC tests to measure learning. Given recent work showing that 2AFC performance correlates with confidence, it is likely that this measure is more related to an explicit representation of learning (Batterink et al., 2015). We therefore sought to also capture more implicit representations using a less direct, reaction time based target detection measure and measure the impact of attention on both kinds of measures at the same time. Here, we demonstrate that in a more complex learning situation people are not automatically able to learn two, unrelated patterns simultaneously without instruction, and that instruction to attend to one or both patterns significantly improves performance on more direct measures, suggesting that this manipulation boosts explicit but not necessarily implicit representations.

Follow up research will explore why the shape and color streams are not learned similarly, especially in the no instruction condition. Even with instruction to learn color, the target detection task never showed learning. Multiple explanations could account for this
difference. As mentioned, the central position of the shapes in relationship to the colors could have given the shape stream a privileged status in participants’ visual field, even when participants were asked to attend to color. It is also possible that participants showed this shape preference because color is a feature and not an object. Its puzzling that we never see indirect learning of this feature. Much future work, looking at streams in isolation and multiple features (not just color) is needed to see whether indirect learning of features is more difficult to observe. Perhaps even more pressing, future work will attempt to have two similar streams (both objects or features) in order to best characterize whether two structures are learnable with no instruction and how instruction impacts the learning of patterns, as expressed on both direct and indirect measures.

Another major difference between the shape and color streams is that color is able to be verbalized in a way that the nonsense shapes used here were not. While it is possible that participants could have generated a name for each of the nine shapes during the experiment and then rehearsed those names, these names would have been less readily available to participants than the names of the colors. A strategy that involved rehearsing the color names when told to attend to color could explain the larger increase in explicit recall scores for color than shape and possibly why indirect learning of color was never observed. Using less-verbalizeable features in future work might lead to interesting insights about how the ability to name aspects of one’s input impacts learning.

Despite these avenues for future research, the present work demonstrates that attention to one’s environment does impact direct measures of statistical learning. How are we to reconcile this with the observation that statistical learning is available to populations that are not advanced in their attentional abilities, like preverbal infants and rats?

First, it is important to realize that many of the studies that have examined the role of attention in statistical learning have used simple patterns that are not necessarily reflective of the type of learning that must happen outside of laboratory settings for this learning mechanism to be a viable explanation for the complex situations many people claim it can account for. Introducing two statistical patterns demonstrates that the complexity of the environment could impact what the role of attention is in successful statistical learning.

Furthermore, the argument that we need attention because infants can use statistical learning rests on the idea that the attentional abilities of young infants are not sophisticated
enough to make use of statistical learning unless it were exclusively implicit and wasn’t helped by attention. But, there is increasing evidence that the allocation of attention in young infants is more sophisticated than originally suggested. For example, infants allocate their attention to elements of their input that are neither so novel they can’t integrate them into their current framework, nor so familiar that they are not able to learn anything else from them; instead, they look longer at elements that are mildly novel (Kidd, Piantadosi, & Aslin, 2014). While this study didn’t examine learning across different novelties, it suggests that the attentional allocation abilities of infants as young as 7 months are more advanced than suggested. Furthermore, it provides support for the link between statistical learning and attention, because of, rather than in spite of, the fact that young infants are able to learn the patterns of their environment. Further research into the link between the development of attentional allocation and its relationship to statistical learning will allow for a better understanding of how statistical learning is able to operate across various age groups, attentional situations, and learning environments that vary in complexity.
References


### Table 4.
LMER Results for Shape and Color Stream Reaction times from Experiments One and Two, Restricted to Position 1 and 2 items.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Shape Stream Learning</th>
<th>Color Stream Learning</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Est.</td>
<td>SE</td>
</tr>
<tr>
<td><strong>No Instructions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Intercept)</td>
<td>0.4565</td>
<td>0.0302</td>
</tr>
<tr>
<td>Detection</td>
<td>-0.00645</td>
<td>0.009654</td>
</tr>
<tr>
<td>Triplet Pos.</td>
<td>-0.013525</td>
<td>0.019646</td>
</tr>
<tr>
<td>Pos. in Task</td>
<td>0.001955</td>
<td>0.002690</td>
</tr>
<tr>
<td>Detection : Triplet Pos.</td>
<td>0.006522</td>
<td>0.006205</td>
</tr>
<tr>
<td>Triplet Pos. : Pos. In Task</td>
<td>-0.001210</td>
<td>0.001680</td>
</tr>
<tr>
<td><strong>Shape Instructions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Intercept)</td>
<td>5.179e-01</td>
<td>3.838e-02</td>
</tr>
<tr>
<td>Detection</td>
<td>-1.909e-02</td>
<td>1.289e-02</td>
</tr>
<tr>
<td>Triplet Pos.</td>
<td>-6.302e-02</td>
<td>2.525e-02</td>
</tr>
<tr>
<td>Pos. in Task</td>
<td>6.660e-04</td>
<td>3.471e-03</td>
</tr>
<tr>
<td>Detection : Triplet Pos.</td>
<td>1.100e-02</td>
<td>8.283e-03</td>
</tr>
<tr>
<td><strong>Color Instructions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Intercept)</td>
<td>0.54585</td>
<td>0.03430</td>
</tr>
<tr>
<td>Detection</td>
<td>-0.011606</td>
<td>0.011697</td>
</tr>
<tr>
<td>Triplet Pos.</td>
<td>-0.078142</td>
<td>0.021393</td>
</tr>
<tr>
<td>Pos. in Task</td>
<td>-0.004411</td>
<td>0.003194</td>
</tr>
<tr>
<td>Detection : Triplet Pos.</td>
<td>0.009672</td>
<td>0.007405</td>
</tr>
<tr>
<td>Triplet Pos. : Pos. In Task</td>
<td>0.004273</td>
<td>0.001828</td>
</tr>
<tr>
<td><strong>Dual Instructions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Intercept)</td>
<td>4.726e-01</td>
<td>3.775e-02</td>
</tr>
<tr>
<td>Detection</td>
<td>-1.717e-02</td>
<td>1.276e-02</td>
</tr>
<tr>
<td>Triplet Pos.</td>
<td>-3.662e-02</td>
<td>2.375e-02</td>
</tr>
<tr>
<td>Pos. in Task</td>
<td>2.474e-03</td>
<td>3.414e-03</td>
</tr>
<tr>
<td>Detection : Triplet Pos.</td>
<td>1.200e-02</td>
<td>7.976e-03</td>
</tr>
<tr>
<td>Triplet Pos. : Pos. In Task</td>
<td>-9.641e-04</td>
<td>2.047e-03</td>
</tr>
</tbody>
</table>

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1
Appendix B.

*Binding Tests:* Participants also completed a series of alternative force choice tests designed to address whether they attempted to combine the statistics of each stream to learn one, larger pattern (which shape could be paired with which color, etc). Higher values on the y-axis in Figures 8, 9, and 10 represent participants having chosen bound items over unbound item.

*Shape Binding (Figure 8):* Participants in the shape and color instructional groups showed at chance performance on tests of shape binding (shape: \( t = -0.45, df = 177, p = 0.65, d = 0.03 \), Color: \( t = -0.23, df = 172, p = 0.82, d = 0.02 \)). Participants in the no-instruction group chose the bound item significantly more than chance (\( t = 2.39, df = 172, p < 0.05, d = 0.18 \)). Participants in the dual instruction group chose the unbound option significantly more than chance (\( t = -2.55, df = 172, p < 0.05, d = 0.19 \)).

![Figure 8. Shape Binding scores by Instructional Condition.](image-url)
**Color Binding (Figure 9):** Participants in the no instruction group, shape instruction group, and dual instruction group all showed no preference for bound or unbound items (no instruction: $t = 0.69, df = 170, p = 0.50, d = 0.05$, Shape: $t = -0.84, df = 170, p = 0.40, d = 0.06$, Dual: $t = -0.30, df = 171, p = 0.76, d = 0.02$). Participants who received instruction to learn the color pattern chose the bound option significantly more than the unbound option ($t = 3.16, df = 176, p < 0.01, d = 0.24$).

![Figure 9. Color Binding Scores by Condition.](image)

**Nonword Binding (Figure 10):** Participants who received no instructions chose the bound item significantly more often than the unbound option ($t = 2.45, df = 29, p = 0.02, d = 0.45$). No other group of participants showed a significant preference for bound or unbound options (Shape: $t = 1.03, df = 29, p = 0.31, d = 0.19$, Color: $t = 1.27, df = 29, p = 0.21, d = 0.23$, Dual: $t = 1.10, df = 29, p = 0.28, d = 0.20$).
Figure 10. Nonword Binding scores by condition.