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Elevated Depressive Symptoms Enhance Reflexive but not Reflective Auditory Category Learning

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Abstract

In vision an extensive literature supports the existence of competitive dual-processing systems of category learning that are grounded in neuroscience and are partially-dissociable. The reflective system is prefrontally-mediated and uses working memory and executive attention to develop and test rules for classifying in an explicit fashion. The reflexive system is striatally-mediated and operates by implicitly associating perception with actions that lead to reinforcement. Although categorization is fundamental to auditory processing, little is known about the learning systems that mediate auditory categorization and even less is known about the effects of individual difference in the relative efficiency of the two learning systems. Previous studies have shown that individuals with elevated depressive symptoms show deficits in reflective processing. We exploit this finding to test critical predictions of the dual-learning systems model in audition. Specifically, we examine the extent to which the two systems are dissociable and competitive. We predicted that elevated depressive symptoms would lead to reflective-optimal learning deficits but reflexive-optimal learning *advantages*. Because natural speech category learning is reflexive in nature, we made the prediction that elevated depressive symptoms would lead to *superior* speech learning. In support of our predictions, individuals with elevated depressive symptoms showed a deficit in reflective-optimal auditory category learning, but an advantage in reflexive-optimal auditory category learning. In addition, individuals with elevated depressive symptoms showed an advantage in learning a non-native speech category structure. Computational modeling suggested that the elevated depressive symptom advantage was due to faster, more accurate, and more frequent use of reflexive category learning strategies in individuals with elevated depressive symptoms. The implications of this work for dual-process approach to auditory learning and depression are discussed.

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Keywords

depressive symptoms; auditory category learning; speech; reflective system; reflexive system

1. Introduction

We report the results from a new line of research that merges a dual-learning systems theoretical framework originally developed in vision (Ashby, Alfonso-Reese, Turken, & Waldron, 1998; Ashby & Maddox, 2005, 2010) and recently extended to audition (Chandrasekaran, Yi, & Maddox, 2013; Maddox & Chandrasekaran, in press; Maddox, Chandrasekaran, Smayda, & Yi, 2013) with research that explores the changes in cognitive processing associated with the presence of elevated depressive symptoms (Beevers, 2005; Beevers et al., 2012; Blanco, Otto, Maddox, Beevers, & Love, 2013; Carver, Johnson, & Joormann, 2009; Maddox, Gorlick, Worthy, & Beevers, 2012). Combining these research areas leads to a set of testable predictions regarding auditory and speech learning in individuals with elevated depressive symptoms.

1.1. Dual-Processes in Visual and Auditory Speech Category Learning

The Competition between Verbal and Implicit Systems (COVIS) theory of visual category learning (Ashby, et al., 1998; Ashby, Paul, & Maddox, 2011) postulates two learning systems, one reflective and one reflexive¹. COVIS offers a rich neurobiologically-based framework for understanding the cognitive and neural processes associated with visual (Ashby, et al., 1998; Ashby & Maddox, 2005, 2010) and auditory category learning (Chandrasekaran, et al., 2013; Maddox & Chandrasekaran, in press; Maddox, et al., 2013). In the introduction we focus exclusively on the cognitive processes and explore the neural mechanisms in the General Discussion.

Briefly, the dual-learning systems model postulates that category learning is mediated by a verbalizable reflective system that is under conscious control and relies on working memory and executive attention, and by a non-verbalizable reflexive system that is not under conscious control and does not rely on working memory and executive attention (Ashby, et al., 1998; Ashby & Maddox, 2005, 2010). The reflective system selects and tests simple verbalizable hypotheses about category membership. To perform well in reflective-optimal tasks, participants must remember which rules they have already tested and rejected in order to avoid revisiting these failed rules again. The reflexive system involves procedurally learning to associate stimuli lying in different regions of perceptual space with different motor responses. The reflective and reflexive systems interact and compete to generate the response on each trial, and learners have an initial bias toward the reflective system, but switch to the reflexive system with practice when that system is the optimal system for solving the task (Ashby, et al., 1998; Ashby, et al., 2011).

¹Recent evidence suggests a third system, referred to as the perceptual-representation system, can also mediate category learning under certain conditions (Casale & Ashby, 2008; Zeithamova, Maddox, & Schnyer, 2008).

1.2. Dual-Processes in Individuals with Elevated Depressive Symptoms

Depression is a common, recurrent, and impairing condition that predicts future suicide attempts, interpersonal problems, unemployment, and substance abuse (Kessler et al., 2003; Kessler & Walters, 1998). Hundreds of millions of individuals currently suffer from depression and many more have elevated depressive symptoms. Furthermore, adults with elevated depressive symptoms, even in the absence of Major Depressive Disorder, have worse physical, social, and role functioning compared to a demographically similar group without a chronic health condition. Indeed, well-being and psychosocial functioning of individuals with elevated depressive symptoms are comparable to people with major chronic medical conditions, such as hypertension, diabetes, and arthritis (Wells et al., 1989).

Individuals with elevated depressives show deficits in tasks that rely on reflective processing, such as problem-solving (Elderkin-Thompson, Mintz, Haroon, Lavretsky, & Kumar, 2006), planning (Rogers et al., 2004), cognitive flexibility (Butters et al., 2004), and decision-making (Beevers, et al., 2012; Blanco, et al., 2013; Clark, Chamberlain, & Sahakian, 2009; Gradin et al., 2011; Maddox, et al., 2012; Murphy et al., 2001; Pizzagalli, Iosifescu, Hallett, Ratner, & Fava, 2008). Much less is known about reflexive processing in individuals with elevated depressive symptoms. However, given the fact that the reflective and reflexive systems compete during learning, we predict that individuals with elevated depressive symptoms will show *enhanced* performance in any category learning task whose learning is mediated by the reflexive system.

To date, category learning has only been explored in individuals with elevated depressive symptoms using the Wisconsin Card Sort Task (Heaton, 1980; Heaton, Chelune, Talley, Kay, & Curtiss, 1993) which is a reflective-optimal category learning task that involves sorting cards into groups based on visually presented features. Individuals with elevated depressive symptoms evidence performance deficits in the Wisconsin Card Sort Task relative to individuals without elevated depressive symptoms (Davis & Nolen-Hoeksema, 2000; Martin, Oren, & Boone, 1991). Auditory category learning has not been explored in individuals with elevated depressive symptoms and thus, the present research represents the first to compare auditory category learning in individuals with and without elevated depressive symptoms in reflective-optimal and reflexive-optimal auditory and speech categories.

1.3. Dual-Processes in Speech Category Learning

In a recent paper, Chandrasekaran, Yi & Maddox (2013) provided strong evidence to suggest that non-native speech category learning is reflexive in nature. Adult, native speakers of American English were trained to learn Mandarin tone categories with trial-by-trial feedback and multiple talkers. Mandarin Chinese has four linguistically-relevant tone categories that differ primarily on the basis of pitch pattern (ma¹ ‘mother’ [T1], ma² ‘hemp’ [T2], ma³ ‘horse’ [T3], ma⁴ ‘scold’ [T4]), described phonetically as ‘high-level’, ‘low-rising’, ‘low-dipping’, and ‘high-falling’ pitch patterns, respectively. Two dimensions (pitch height and pitch direction) serve as primary cues in categorizing tones, and these cues are differentially weighted across languages (Gandour & Harshman, 1978). Critically, three experimental manipulations (timing of feedback, richness of feedback, and extent of talker

variability) were introduced that, based on COVIS, that should enhance reflective-system or reflexive-system processing. COVIS predicts that delayed feedback, rich information content during feedback, and blocked talker (low talker variability) conditions should enhance reflective-system processing whereas immediate feedback, minimal information content and mixed talker conditions should enhance reflexive-system processing (Maddox, Ashby, & Bohil, 2003; Maddox & Ing, 2005; Maddox, Love, Glass, & Filoteo, 2008). Performance was superior when feedback was immediate, information content was minimal and talkers were mixed. These results converge and provide strong evidence to suggest that non-native speech category learning is reflexive-optimal.

1.4. Overview of Studies and Predictions

Based on the Chandrasekaran et al (2013) work, we make the prediction that elevated depressive symptoms will lead to *enhanced* non-native speech category learning relative to non-elevated depressive symptoms. We test these predictions in two experiments. Experiment 1 examines learning of reflective-optimal and reflexive-optimal, experimenter-constrained auditory categories in individuals with and without elevated depressive symptoms. Experiment 2 examines non-native speech category learning that utilizes naturally produced Mandarin tone categories as stimuli in individuals with and without elevated depressive symptoms. We predict that individuals with elevated depressive symptoms will show a deficit in the reflective-optimal auditory category learning task, but an *advantage* in the reflexive-optimal auditory category learning task. In addition, we predict that individuals with elevated depressive symptoms will show an *advantage* in the Mandarin tone, speech category learning task. In addition to simple measures of accuracy, Experiment 2 will utilize a recently developed computational modeling approach that can be applied to Mandarin tone learning (Maddox & Chandrasekaran, in press). Computational modeling is valuable because it provides a window onto the nature of cognitive processing that is not available through an examination of simple performance measures such as accuracy.

2. Experiment 1

Experiment 1 examines reflective-optimal and reflexive-optimal auditory category learning in individuals with and without elevated depressive symptoms. We predict a deficit in reflective-optimal auditory category learning, but enhanced reflexive-optimal auditory category learning in individuals with, relative to those without, elevated depressive symptoms.

2.1. Method

2.1.1. Participants—Two hundred seventeen individuals from the greater Austin, Texas community were paid \$10 per hour for their participation with 106 participating in the reflective-optimal auditory category learning task and 111 participating in the reflexive-optimal auditory category learning condition (Table 1). Participants were recruited using flyers posted in the community and ads posted on the Web. Interested participants were asked demographic questions and were screened for the presence of depressive symptoms. We then actively recruited individuals with and without elevated depressive symptoms

(defined below) to serve in the study. The experiment was approved for ethics procedures using human participants and informed consent was obtained from all participants. Groups of individuals with and without elevated depressive symptoms did not differ significantly in age, gender ratio, tone language experience, or music training: the age at which the participant began music practicing, years of practice, and hours practiced per week. Music training questions were included because music training has been found to enhance speech category learning (Alexander, Wong, & Bradlow, 2005; Lee & Hung, 2008). Stimuli were presented at comfortable supra-threshold listening levels, as judged by the participants.

2.1.2. Elevated Depressive Symptom Classification—At the beginning of the experimental session, each participant was administered the Center for Epidemiological Studies Depression Scale (CES-D; Radloff, 1977). Following convention (Weissman, Sholomskas, Pottenger, Prusoff, & Locke, 1977), participants who obtained a score of 16 or greater were classified as having elevated depressive symptoms and those with a score of 15 or less were classified as not having elevated depressive symptoms. CES-D scores of 16 or greater reflect mild or greater symptoms of depression (Radloff, 1977). Major Depressive Disorder (MDD), medication history, therapy history, and comorbid mental or physical health problems were not assessed. Although some individuals in the sample may have met MDD criteria, individuals with subthreshold MDD nevertheless experience significant functional impairment (Broadhead, Blazer, George, & Tse, 1990; Johnson, Weissman, & Klerman, 1992), are more likely to have a family history of MDD (Kendler & Gardner, 1998), and are more likely to be diagnosed with MDD in the future (Horwath, Johnson, Klerman, & Weissman, 1992; Kendler & Gardner, 1998) compared to individuals with relatively low depression symptoms. Further, comparing groups who have or do not have elevated depressive symptoms is consistent with prior research (e.g., Beevers, Clasen, Stice, & Schnyer, 2010; Harle, Allen, & Sanfey, 2010; Maddox, et al., 2012; Pizzagalli, Jahn, & O'Shea, 2005).

2.1.3. Stimuli—Stimuli consisted of auditory tones presented via headphones. Each stimulus was four dimensional with one of two possible values for each dimension being presented (16 stimuli total). The stimuli varied along the four auditory dimensions of duration (long vs. short; 500 ms vs. 250 ms), number (1 vs. 2 non-overlapping tones), pitch (high vs. low; 180 Hz vs. 80 Hz), and vowel (/a/ vs. /i/). In the reflective-optimal task, categories were defined by arbitrarily making two stimulus dimensions relevant (e.g., pitch and number), and two stimulus dimensions irrelevant (e.g., duration and vowel). For the two relevant dimensions the binary properties of each dimension were arbitrarily given the values 1 or -1 (e.g., high pitch = 1 and low pitch = -1; one tone = 1 and two tones = -1). Stimuli in category A were those with values of 1 on both relevant dimensions (one high pitch tone) or values of -1 on both relevant dimensions (two low pitch tones). Stimuli in category B were those with a value of 1 on one relevant dimension and a value of -1 on the other relevant dimension (one low pitch tone or two high pitch tones). A schematic of one possible reflective-optimal problem is displayed in Figure 1a.

In the reflexive-optimal task, we first made one stimulus dimension irrelevant (e.g. duration). Then for the three remaining relevant stimulus dimension, the possible properties

of each stimulus were given a value of 1 or -1 (e.g. for pitch, high = 1 and low = -1). Then, each category structure was created by the following mathematical formula (where the three relevant stimulus dimensions are X, Y, and Z):

If $X + Y + Z > 0$, then “A,” else “B.”

A schematic of one possible reflexive-optimal problem is displayed in Figure 1b.

2.1.4. Procedure—Participants performed the experiment on a personal computer in a well-controlled testing room. Sennheiser HD 280 Pro headphones were used to present the stimuli. Participants were informed that they would be listening to sounds that vary across trials in duration, pitch, vowel, and number of tones. They were informed that each sound was a member of one of two categories: A or B, and that their task was to determine the category membership for each sound by using the computer key and pressing either the “z” button which corresponded to category A or the “m” button which corresponded to category B. Participants were informed that they would receive feedback following each response that would state whether their response was “correct” or “incorrect”. Finally, they were informed that their goal was to generate 10 correct responses in a row. Once they achieved 10 correct responses in a row, or after 200 trials, whichever came first, the task would end.

2.2. Results

The primary dependent measure was the trials-to-reach the criterion of 10 correct responses in a row. If an individual did not reach criterion after 200 trials, we assumed a trials-to-criterion of 200 (Maddox, et al., 2013). Figure 2 displays the average trials-to-criterion for the individuals with and without elevated depressive symptoms in the reflective-optimal and reflexive-optimal auditory category learning tasks. A 2 participant group $\times$ 2 task between-groups ANOVA was conducted on the trials-to-criterion measure. The main effect of task was significant [$F(1, 213) = 5.94, p = .016$, partial $\eta^2 = .027$], whereas the main effect of participant group was not [$F(1, 213) = .01, p = .92$, partial $\eta^2 = .000$]. Importantly, there was a significant interaction between participant group and task [$F(1, 213) = 9.54, p = .002$, partial $\eta^2 = .043$]. As expected, individuals with elevated depressive symptoms took significantly more trials to reach criterion in the reflective-optimal task than individuals without elevated depressive symptoms [$t(104) = 2.10, p = .038$, partial $\eta^2 = .041$]. Also as predicted, the reverse pattern held in the reflexive-optimal task with individuals with elevated depressive symptoms taking significantly more trials than individuals without elevated depressive symptoms to reach criterion [$t(109) = 2.28, p = .025$, partial $\eta^2 = .045$]. Interestingly, the rate of learning did not differ across tasks for individuals without elevated depressive symptoms [$t(146) = .57, p = .57$, partial $\eta^2 = .002$], but the learning rate was significantly faster in the reflexive-optimal than in the reflective-optimal task for individuals with elevated depressive symptoms [$t(67) = 3.37, p = .001$, partial $\eta^2 = .145$].

2.3. Summary

As predicted from the auditory version of COVIS and from previous work showing a deficit in reflective processing for individuals with elevated depressive symptoms, we found that these individuals were slower to learn the reflective-optimal auditory categories, but were faster to learn the reflexive-optimal auditory categories than individuals without elevated

depressive symptoms. In addition, the fact that learning rates for the reflective-optimal and reflexive-optimal tasks did not differ in individuals without elevated depressive symptoms, but were higher for individuals with elevated depressive symptoms in the reflexive-optimal task, suggests that the interaction of depressive symptom status with task performance is being driven by changes in reflective and reflexive processing in individuals with elevated depressive symptoms and not in individuals without elevated depressive symptoms. We turn now to Experiment 2 that examines natural speech category learning in individuals with and without elevated depressive symptoms.

3. Experiment 2

Learning new speech categories as an adult is considered a difficult task. However, listeners can be trained to acquire even difficult to learn speech categories. Laboratory-based training programs have ubiquitously used feedback to enhance learning. Recent work suggests that the dynamics of feedback is a critical determiner of category learning success (Chandrasekaran, et al., 2013; Lim & Holt, 2011; Seitz et al., 2010). In a previous study, we demonstrated that feedback dynamics that targeted the reflexive learning system enhanced second language (L2) speech category learning success, relative to those that targeted the reflective learning system. In the current experiment we examine L2 speech category learning in individuals with and without elevated depressive symptoms using exemplars from Mandarin Chinese, a tone language. Two dimensions, pitch height, and pitch direction are important for discerning tone categories across languages. For example, on the pitch height-pitch direction continuum, the four Mandarin tone categories can be differentiated as “high-level”, “low-rising”, “low-dipping”, and “high-falling”. The pitch height dimension (average pitch across the syllable) is important for distinguishing low tones from high tones; the pitch direction dimension is important in distinguishing rising tones from falling tones.

Five monosyllabic Mandarin Chinese words (*bu*, *di*, *lu*, *ma*, and *mi*) that are minimally contrasted by the four tone categories were used in the experiment, and each was produced in citation form with the four Mandarin tones by two male and two female native speakers of Mandarin Chinese. This yielded a total of 80 unique exemplars. A scatter-plot of these 80 stimuli in the two-dimensional pitch height-pitch direction space is displayed in Figure 3a. Scatter-plots of the 40 stimuli spoken by a two male and two female speakers are displayed in Figures 3b and 3c, respectively. Note that no simple reflective rule-based strategy can be applied to accurately separate the stimuli into the four tone categories. Rather a reflexive, information-integration strategy is necessary.

Because reflexive processes are needed to optimize learning, and because individuals with elevated depressive symptoms are hypothesized to show enhanced reflexive processing, we predict that individuals with elevated depressive symptoms will show a performance advantage relative to individuals without elevated depressive symptoms in this task. To test this prediction, we compare accuracy rates across groups of individuals with and without elevated depressive symptoms. Although accuracy rates are useful, they tell us little about the strategies that individuals are using to solve the task. This follows because a number of reflective and reflexive strategies exist that yield the same accuracy rate. To examine strategy differences across groups, we will utilize neurobiologically-inspired computational

models of reflective and reflexive processing that have been applied extensively to category learning data (Ashby & Maddox, 1993; Maddox & Ashby, 1993), and recently were extended to Mandarin tone category learning (Maddox & Chandrasekaran, in press).

3.1.Method

3.1.1. Participants and Elevated Depressive Symptom Classification—Sixty-five individuals from the greater Austin, Texas community were recruited using the methods outlined in Experiment 1 and were paid \$10 per hour for their participation (Table 2). The classification scheme outlined in Experiment 1 was applied in Experiment 2 and resulted in 30 individuals being classified as having elevated depressive symptoms and 35 participants being classified as having non-elevated depressive symptoms. The experiment was approved for ethics procedures using human participants and informed consent was obtained from all participants. Depressive symptom groups did not differ significantly in age, gender ratio, tone language experience or music training; the age at which the participant began music practicing, years of practice, and hours practiced per week. Music training questions were included because music training has been found to encourage speech category learning (Alexander, et al., 2005; Lee & Hung, 2008). Stimuli were presented at comfortable supra-threshold listening levels, as judged by the participants.

3.1.2. Stimulus Characteristics—Stimuli consisted of natural native exemplars of the four Mandarin tones, tone 1 (T1), tone 2 (T2), tone 3 (T3), and tone 4 (T4). Monosyllabic Mandarin Chinese words (*bu*, *di*, *lu*, *ma*, and *mi*) that are minimally contrasted by the four tone categories were used in the experiment. Since these syllables exist in the American English inventory, the use of these stimuli circumvents the need to learn phonetic structures additional to the tone distinction (Alexander, et al., 2005). By using different segments and multiple talkers, our aim is to expose learners to variability inherent in natural language. Each of these syllables was produced in citation form with the four Mandarin tones. Talkers consisted of native speakers ($N = 4$; 2 f) of Mandarin Chinese originally from Beijing. Stimuli were RMS amplitude and duration normalized (70 dB, 0.4 s) using the software Praat (Alexander, et al., 2005; Perrachione, Lee, Ha, & Wong, 2011; Wong, Perrachione, Gunasekera, & Chandrasekaran, 2009). Duration and amplitude envelope are potentially useful cues to disambiguate lexical tones. However, behavioral studies (Howie, 1976) as well as multidimensional scaling (MDS) analyses have shown that dimensions related to pitch, especially height and direction, are used primarily to distinguish tone categories (Francis, Ciocca, Ma, & Fenn, 2008). Five native speakers of Mandarin were asked to identify the tone categories (they were given four choices) and rate their quality and naturalness. High identification (>95%) was achieved across all 5 native speakers. Speakers rated these stimuli as highly natural. A scatter-plot of the 80 stimuli in the pitch height-pitch direction space is displayed in Figure 3a.

3.1.3. Procedure—On each trial, participants were presented with a single exemplar from one of four Mandarin tone categories (T1, T2, T3, or T4) and instructed to categorize the stimulus into one of four equally likely categories. Participants were given feedback on each trial and exposed to multiple talkers throughout the training program. Participants listened to each of the 80 unique stimuli (4 tone categories X 5 syllables X 4 talkers) once in each block

in a random order, and completed a total of six blocks of training. Participants were instructed that high levels of accuracy were possible but that the task would be difficult and would take practice. Participants generated a response by pressing one of four number button keys on the left side of the computer keyboard, labeled “1”, “2”, “3”, or “4”. Following the response, corrective feedback was provided for 1 s on the computer screen and consisted of the word “Correct.” or “No.” followed by the label of the tone that was actually presented. For example, on a correct T2 trial the feedback display was as follows: “Correct, that was a category 2”. On an incorrect response trial where T3 was the correct response the feedback display was as follows: “No, that was a category 3”. A 1-s ITI followed the feedback.

3.2. Accuracy Results

We first present accuracy analyses comparing block-by-block performance across groups of individuals with and without elevated depressive symptoms, and then we present model-based analyses to explore the types of strategies that participants use to solve the task.

We conducted a 2 participant group 6 block mixed design ANOVA on the accuracy data. The main effect of participant group was significant [$F(1, 63) = 5.19$, $p = .026$, partial $\eta^2 = .076$] and suggested that individuals with elevated depressive symptoms were more accurate than individuals without elevated depressive symptoms at the speech category learning task. The main effect of block was also significant [$F(5, 315) = 55.31$, $p < .001$, partial $\eta^2 = .467$]. The interaction between participant group and block was non-significant [$F(5, 315) = 1.47$, $p = .20$, partial $\eta^2 = .023$]. The main effect of participant group is displayed graphically in Figure 4 along with learning curves in the inset.

3.3. Modeling Results

The accuracy-based analyses suggest a performance advantage for individuals with elevated depressive symptoms over individuals without elevated depressive symptoms in Mandarin tone category learning. This pattern of results is predicted from the dual-learning systems framework and our understanding of the adverse effects of elevated depressive symptoms on processing in the reflective system. The accuracy results are informative, but tell us nothing about the processing locus of this elevated depressive symptom advantage. Specifically, it is of interest to determine whether individuals with elevated depressive symptoms are using reflexive processing strategies to a greater degree, and if so whether they are also using these more accurately. To answer these questions we turn to computational modeling techniques that provide the necessary window onto cognitive processing.

3.3.1. Computational Modeling Details—We fit a series of decision-bound models on a block-by-block basis at the individual participant level because of problems with interpreting fits to aggregate data (Ashby, Maddox, & Lee, 1994; Estes, 1956; Maddox, 1999). We assume that the two-dimensional space (pitch height vs. pitch direction) displayed in Figure 3a accurately describes the perceptual representation of the stimuli. Based on the results from our earlier work (Maddox & Chandrasekaran, in press) that showed that participants can categorize by the sex of the speaker (male/female) with greater than 95% accuracy with no feedback, we also assumed that participants applied category

learning strategies separately to the male (Figure 3b) and female (Figure 3c) perceptual spaces. Note that as long as the major dimensions are known, these modeling procedures can be applied to any type of speech category structure so this offers an exciting new approach to the study of speech category learning.

Here we provide a brief description of each model, as well as an interpretation of the model results. Details are available in numerous previous publications (e.g., Ashby & Maddox, 1993; Maddox & Ashby, 1993; Maddox & Chandrasekaran, in press). Each model assumes that decision-bounds were used to classify stimuli into each of the four Mandarin tone categories (T1, T2, T3, or T4). We applied three classes of models. The first is a computational model of the reflexive category learning system. This is instantiated with the Striatal Pattern Classifier (SPC; Ashby & Waldron, 1999). The SPC is a computational model whose processing is consistent with the neurobiology of the reflexive category learning system and is thought to underlie reflexive-optimal classification performance (Maddox & Chandrasekaran, in press; Nomura et al., 2007; Seger & Cincotta, 2005). Responses from a hypothetical participant using the SPC are displayed in Figure 5a. The second class is models of the reflective category learning system (Ashby & Waldron, 1999). A number of conjunctive and uni-dimensional reflective models were examined. Conjunctive models assume that the participant sets criteria along the pitch height and pitch direction dimensions that are then combined to determine category membership. Responses from a hypothetical participant using a conjunctive strategy are displayed in Figure 5b. Uni-dimensional models assume that the participant sets criteria along the pitch height or pitch direction dimension that are then used to determine category membership. Responses from a hypothetical participant using a uni-dimensional strategy along pitch height are displayed in Figure 5c, and responses from a hypothetical participant using a uni-dimensional strategy along pitch direction are displayed in Figure 5d. The third model is a random responder model that assumes that the participant guesses on each trial. Each model was fit to each block of 80 trials assuming the fixed perceptual space in Figures 3b (male talkers) and 3c (female talkers).

The models were fit to the Mandarin tone category learning data from each trial by maximizing negative log-likelihood and the best fitting model was identified by comparing AIC values for each model (Akaike, 1974). AIC penalizes models with more free parameters. For each model, i , AIC is defined as:

$$AIC_i = -2\ln L_i + 2V_i \quad (1)$$

where L_i is the maximum likelihood for model i , and V_i is the number of free parameters in the model. Smaller AIC values indicate a better fit to the data.

3.3.2. Computational Modeling Results—The accuracy-based analysis provided support for the strong prediction that individuals with elevated depressive symptoms will evidence better speech learning because their impaired reflective processing leads to enhanced reflexive processing. This follows because reflexive strategies yield higher accuracy in speech learning situations. As a more direct test of this hypothesis we examined a number of aspects of the modeling results. First, we determined the first block of trials for

which the SPC (a model of reflexive processing) provided the best fit of the data. If individuals with elevated depressive symptoms show enhanced reflexive processing then they should use reflexive strategy sooner than individuals without elevated depressive symptoms. Second, we determined the total number of blocks (out of 6) for which the SPC provided the best account of the data. If individuals with elevated depressive symptoms show enhanced reflexive processing then they should use reflexive strategies (as measured by the SPC) in more blocks of trials. Data from these two measures is displayed in Figure 6. As predicted, individuals with elevated depressive symptoms use a reflexive strategy significantly sooner (after 3.33 blocks on average) than individuals without elevated depressive symptoms (after 4.86 blocks on average) [$t(63) = 2.78, p = .007$]. In addition, individuals with elevated depressive symptoms use a reflexive strategy in significantly more blocks (2.50 blocks on average) than individuals without elevated depressive symptoms (1.57 blocks on average) [$t(63) = 1.99, p = .05$].

These findings establish that individuals with elevated depressive symptoms use reflexive strategies sooner and with greater regularity than individuals without elevated depressive symptoms. Next we ask whether they also use these strategies more accurately. As a test of this hypothesis we first identified individuals with and without elevated depressive symptoms whose final block of data was best fit by the SPC (50% and 40% of individuals with and without elevated depressive symptoms, respectively). We then examined overall accuracy rates across the two participant groups, as well as accuracy rates during only the last half of the study (specifically blocks 4 – 6) when reflexive strategies dominated. Data from these two measures are displayed in Figure 7. Individuals with elevated depressive symptoms were significantly more accurate than individuals without elevated depressive symptoms based on overall accuracy [$t(27) = 2.43, p = .022$], and accuracy during the last half of the study [$t(27) = 2.18, p = .038$].

For completeness we also explored the strategies used by participants whose data was not best fit by the SPC in the final block of trials. The overwhelming majority of these participants used a uni-dimensional strategy that focused on pitch height (40% and 54% of individuals with and without elevated depressive symptoms, respectively). Overall accuracy rates did not differ across groups (average proportion correct = .46 and .43 for individuals with and without elevated depressive symptoms, respectively), and accuracy rates during the last half of the study did not differ across group (average proportion correct = .47 and .48 for individuals with and without elevated depressive symptoms, respectively).

3.4. Summary

Experiment 2 examined the strong prediction that individuals with elevated depressive symptoms should show a learning *advantage* when faced with the task of learning non-native speech categories, which we predicted were reflexive-optimal. Not only were individuals with elevated depressive symptoms more accurate, but the locus of this accuracy advantage was due to earlier and more frequent use of the optimal reflexive processing system. In addition, when we focused only on individuals with and without elevated depressive symptoms who used the reflexive system by the end of the task, individuals with elevated depressive symptoms were more accurate overall, when reflexive processing

dominated. This suggests that not only are individuals with elevated depressive symptoms faster to use reflexive-optimal processing, but that they use these strategies more accurately.

4. General Discussion

To our knowledge this is the first study to explore auditory and speech category learning in individuals with and without elevated depressive symptoms. In exploring the relationship between the dual-learning system approach to category learning, which postulates a working memory and executive attention intensive reflective-system that is complemented by a more automatic, procedural reflexive system that does not require working memory or executive attention, and dual-system processing in individuals with and without elevated depressive symptoms, we identified a set of strong predictions. Specifically, we predicted a deficit in reflective-optimal auditory category learning but an *advantage* in reflexive-optimal auditory category learning for individuals with elevated, relative to non-elevated, depressive symptoms. Because there is evidence to suggest that non-native natural speech category learning is reflexive in nature (Chandrasekaran, et al., 2013; Lim & Holt, 2011), we made the prediction that individuals with elevated depressive symptoms would also be superior at natural speech category learning.

We tested our predictions in two experiments. Experiment 1 examined reflective-optimal and reflexive-optimal auditory category learning in individuals with and without elevated depressive symptoms. As predicted, individuals with elevated depressive symptoms showed a deficit in reflective-optimal auditory category learning, but an advantage in reflexive-optimal auditory category learning. In addition, the cross over interaction was driven solely by the improved learning of individuals with elevated depressive symptoms in the reflexive-optimal condition relative to the reflective-optimal condition. Experiment 2 examined non-native speech (Mandarin tone) category learning in individuals with and without elevated depressive symptoms. As predicted, we found an advantage in speech category learning for individuals with elevated depressive symptoms. Computational model-based analyses suggested that the locus of this performance advantage was due to faster, and more frequent, use of reflexive-processing strategies. In addition, individuals with elevated depressive symptoms who used reflexive processing by the end of the task were more accurate overall, and during the last half of the study than individuals with non-elevated depressive symptoms who used reflexive processing by the end of the task. This suggests that not only are individuals with elevated depressive symptoms faster to use reflexive-optimal processing, but that they use these strategies more accurately. The implications of this work are many and are broad-based. We briefly discuss some of these below.

4.1. Implications for Dual-Learning Systems Approach to Depression

In addition to providing important insights onto the nature of dual-learning systems in auditory category learning, this work also has strong implications for depression and the influence of elevated depressive symptoms on cognitive processing. These data provide strong support for the notion that elevated depressive symptoms, known to adversely affect a number of important aspects of reflective processing, adversely affect reflective-optimal auditory category learning. What is novel and may have strong practical importance is the

fact that these data also suggest that poor processing in the reflective system leads to *enhanced* processing in the reflexive system.

Although the focus of the current study was on individuals with elevated depressive symptoms, we posit that this work has strong implications for individuals with MDD as well. It is well established that individuals with MDD often have concrete, rigid, and generally inflexible thinking patterns (Joormann, Levens, & Gotlib, 2011; Nolen-Hoeksema, Wisco, & Lyubomirsky, 2008). These are often linked to executive dysfunction (Castaneda, Tuulio-Henriksson, Marttunen, Suvisaari, & Lonnqvist, 2008) and are likely due to altered frontal cortical functioning (Carpenter, Just, & Reichle, 2000). This is exactly the pattern of neural and cognitive processing that would be associated with better reflexive and worse reflective styles for auditory category learning. Future work should test this hypothesis directly.

Other more broad based implications of this work are likely. First, many important cognitive tasks that require reflective processing can also be solved, or at the very least they can be “bootstrapped”, with reflexive processing. Thus, one focus for future research should be on developing optimized tools for using reflexive processing to enhance performance in tasks that generally rely on reflective processing. Second, if elevated depressive symptoms lead to enhanced reflexive processing, then one could envision using mild negative mood inductions to enhance learning when the task relies heavily on reflexive processing (e.g., L2 learning).

4.2.Critical Test of Auditory Dual-Learning Systems Approach

From a theoretical perspective, the neurobiologically-constrained dual-learning systems framework has been almost exclusively evaluated using visual categories. The COVIS model (COVIS; Ashby, et al., 1998), explicitly states that it is a model of *visual* category learning. Ashby and colleagues suggest that connection patterns between the visual system and the striatum may be quantitatively different from the connections between the auditory system and the striatum (Ashby & Valentin, 2005). In a recent paper, we (Maddox & Chandrasekaran, in press) reviewed the results from anatomical studies in non-human animals that suggest the primary and association auditory cortical regions are strongly connected to the reflective and reflexive systems (Figure 2). Specifically, retrograde anatomical labeling studies in primates show that the primary and association cortices are connected to the prefrontal cortex via dorsal and ventral routes, which are key areas in the reflective learning system (Figure 2a) (Petrides & Pandya, 1988; Yeterian & Pandya, 1998). In addition, many-to-one convergent projections from secondary auditory areas connect to the posterior caudate/putamen (Figure 2b) (Petrides & Pandya, 1988; Yeterian & Pandya, 1998) — key areas in the reflexive learning system (Ashby & Ennis, 2006; Waldschmidt & Ashby, 2011). Taken together, these studies lend neurobiological plausibility to the application of a dual-systems framework in the auditory domain.

Thus far, auditory category learning has been examined largely as an emergent property of unsupervised or supervised learning processes (Goudbeek, Cutler, & Smits, 2008; McClelland, Fiez, & McCandliss, 2002; Norris, McQueen, & Cutler, 2003; Toscano & McMurray, 2010; Vallabha, McClelland, Pons, Werker, & Amano, 2007). During

unsupervised learning, categories emerge in the auditory association cortices through an implicit process involving Hebbian learning (Guenther, Nieto-Castanon, Ghosh, & Tourville, 2004; Vallabha & McClelland, 2007). More recently, computationally based unsupervised learning models have incorporated competition in addition to statistical learning (McMurray, Aslin, & Toscano, 2009; Toscano & McMurray, 2010). From the neurobiological perspective, unsupervised category learning is instantiated within topographical maps in the primary and secondary auditory regions that are sensitive to input statistics (Guenther, et al., 2004; Vallabha & McClelland, 2007). This is very similar in spirit to the perceptual representation category learning system that has been explored in the visual domain (Aizenstein et al., 2000; Ashby & O'Brien, 2005; Reber, Stark, & Squire, 1998a; Reber, Stark, & Squire, 1998b; Zeithamova, et al., 2008). In vision, the perceptual representation system is thought to rely on implicit, unsupervised Hebbian learning within the occipital cortex (Aizenstein, et al., 2000; Ashby & O'Brien, 2005; Reber, et al., 1998a; Reber, et al., 1998b; Zeithamova, et al., 2008).

Theorizing about unsupervised learning in the auditory domain is important, but is critically different from theorizing about feedback-dependent (supervised) learning. Supervised learning models posit that feedback (lexical or selective attention) to the sensory network is necessary, in addition to the implicit Hebbian learning process (Norris, et al., 2003). Although significant unsupervised speech learning can occur in adults, category learning *with feedback* can lead to substantially *larger* gains in category learning (Goudbeek, et al., 2008; McClelland, et al., 2002). In the auditory domain, there has been less focus on the role of the dual-learning systems that are responsive to *feedback*. This is despite the fact that functional neuroimaging studies examining speech category learning in adults implicate reflective and reflexive learning circuitry in addition to the auditory regions (Callan et al., 2003; Tricomi, Delgado, McCandliss, McClelland, & Fiez, 2006). In dual-learning systems models, reflective rules are encoded within the sensory areas with bidirectional connections to working memory units within the lateral portion of the prefrontal cortex (PFC). When a new rule is generated, the excitatory input from the PFC to the head of the caudate is strengthened, resulting in the maintenance of a newly established rule. The PFC units that each represents a particular rule are activated by the anterior cingulate to select among various alternative rules. In comparison, during reflexive learning, a single striatal unit (or small group of units) implicitly associates an abstract cortical-motor response with a large group of sensory cells. The critical aspect of learning occurs at cortical-striatal synapses, and synaptic plasticity is facilitated by a dopamine-mediated reinforcement training signal. Despite the different circuitries, both the reflective and reflexive learning systems utilize the sensory component within the primary and association auditory regions. These components are reflectively or reflexively associated with rewards (e.g., instructional feedback).

Data from the current study provides the first critical test of two predictions derived from the dual-learning systems approach to auditory category learning: the dissociable nature of the systems and the competition between systems, and thus provide strong support for the dual-learning system model of auditory category learning. Importantly, these tests were realized using an individual difference measure, the number of depressive symptoms that is important in its own right. The finding that individuals with elevated depressive symptoms,

known to adversely affect a number of aspects of reflective processing, show enhanced reflexive-optimal auditory and speech category learning but show attenuated reflective-optimal auditory category learning supports the notion of dissociable systems and the notion that the systems are in competition.

4.3.Limitations

Several limitations of the current study should be noted. First, we did not complete diagnostic interviews. In addition, because we did not screen for major depression, it is unknown whether clinically depressed individuals would perform similarly on the category learning tasks used in this study. All individuals with elevated depressive symptoms exceeded a cut-point on the CES-D commonly used to screen for major depressive disorder (Radloff, 1977); however, it is likely that many participants would not have met criteria for a major depressive episode. Second, we did not measure IQ, collect educational status, or assess other factors that might influence category learning. Finally, we do not know if findings will generalize to other tasks, including other category learning tasks. Determining the boundary conditions for these associations will require more comprehensive testing. Despite these limitations, this work provides important new insight into auditory and speech category learning and the influence of elevated depressive symptoms in this domain.

4.4.Conclusions

This represents the first study to comprehensively examine auditory and speech category learning in individuals with elevated depressive symptoms. As predicted from our application of dual-learning systems theory to auditory category learning, and from the extensive literature suggesting elevated depressive symptoms deficits in reflective processing, we hypothesized that individuals with elevated depressive symptoms would show a reflexive-optimal auditory category learning deficit, but a reflexive-optimal auditory category learning advantage relative to individuals without elevated depressive symptoms. In support of our prediction, we found that individuals with elevated depressive symptoms showed a reflexive-optimal auditory category learning deficit, but a reflexive-optimal auditory category learning advantage. Because natural speech category learning is thought to be reflexive, we also predicted and found support for the hypothesis that individuals with elevated depressive symptoms would show a natural speech category learning advantage. Computational modeling suggested that this performance advantage was due to faster and more frequent use of reflexive category learning strategies that were also used more accurately by individuals with elevated depressive symptoms.

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Figure 1.

(A) A schematic of one possible reflective-optimal problem in which the pitch (High or Low) and duration (Long or Short) dimensions are relevant. (B) A schematic of one possible reflective-optimal problem in which the duration dimension (Long or Short) is irrelevant.

Figure 2.

Trials-to-criterion for non-depressive and depressive participants in the reflective-optimal and reflexive-optimal non-speech auditory category learning task from Experiment 1. Standard error bars included.

Figure 3.

(A) Scatterplot of all stimuli from Experiment 2. (B) Scatterplot of male-talker stimuli from Experiment 2. (C) Scatterplot of female-talker stimuli from Experiment 2. Stimuli dimensions (Pitch Height and Pitch Direction) were normalized between 0 and 1.

Figure 4. Proportion correct (averaged across blocks) for non-depressive and depressive participants in the Mandarin tone category learning task from Experiment 2. Standard error bars included. (Inset) Learning curves for non-depressive and depressive participants in the Mandarin tone category learning task from Experiment 2.

Figure 5. Scatterplots of the responses along with the decision boundaries that separate response regions from a hypothetical participant using a version of the (A) Striatal Pattern Classifier, (B) Conjunctive rule-based, (C) Uni-Dimensional_Height, and (D) Uni-Dimensional_Direction models as applied to the female talker stimuli shown in Fig 3c.

Figure 6. (left) First block during which non-depressive and depressive participants first used a strategy consistent with reflexive processing (i.e., the SPC). (right) Total number of blocks during which non-depressive and depressive participants first used a strategy consistent with reflexive processing. Standard error bars included.

Figure 7. (left) Overall accuracy and (right) Block 4 – 6 accuracy for non-depressive and depressive participants whose final block of data was best fit by a strategy consistent with reflexive processing (i.e., the SPC). Standard error bars included.

Table 1

Experiment 1 Demographic Characteristics

	Non-Depressive		Depressive	
	Reflective	Reflexive	Reflective	Reflexive
N	72	76	34	35
Age: mean (sd)	26.17 (2.12)	24.24 (4.59)	25.52 (4.29)	24.71 (4.52)
Gender (m/f)	36/36	33/43	16/18	16/19
CES-D: mean (sd)	6.28 (4.22)	6.35 (4.11)	21.65 (6.16)	20.83 (4.52)
CES-D: range	0–15	0–15	16–47	16–33

Table 2

Experiment 2 Demographic Characteristics

	Non-Depressive	Depressive
N	35	30
Age: mean (sd)	19.35 (3.11)	19.17 (2.37)
Gender (m/f)	8/27	11/19
CES-D: mean (sd)	7.91 (3.47)	25.10 (7.07)
CES-D: range	0–15	16–43