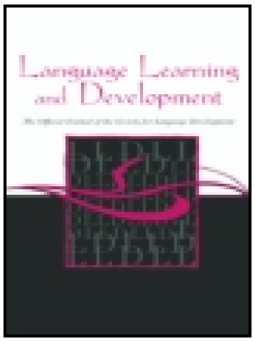

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Change Is Hard: Individual Differences in Children's Lexical Processing and Executive Functions after a Shift in Dimensions

Ron Pomper[a,b], Margarita Kaushanskaya[b,c], and Jenny Saffran[a,b]

[a]Department of Psychology, University of Wisconsin-Madison, Madison, Wisconsin, USA; [b]Waisman Center, University of Wisconsin-Madison, Madison, Wisconsin, USA; [c]Department of Communication Sciences and Disorders, University of Wisconsin-Madison, Madison, Wisconsin, USA

ABSTRACT

Language comprehension involves cognitive abilities that are specific to language as well as cognitive abilities that are more general and involved in a wide range of behaviors. One set of domain-general abilities that support language comprehension are executive functions (EFs), also known as cognitive control. A diverse body of research has demonstrated that EFs support language comprehension when there is conflict between competing, incompatible interpretations of temporarily ambiguous words or phrases. By engaging EFs, children and adults are able to select or bias their attention toward the correct interpretation. However, the degree to which language processing engages EFs in the absence of ambiguity is poorly understood. In the current experiment, we tested whether EFs may be engaged when comprehending speech that does not elicit conflicting interpretations. Different components of EFs were measured using several behavioral tasks and language comprehension was measured using an eye-tracking procedure. Five-year-old children (n = 56) saw pictures of familiar objects and heard sentences identifying the objects using either their names or colors. After a series of objects were identified using one dimension, children were significantly less accurate in fixating target objects that were identified using a second dimension. Further results reveal that this decrease in accuracy does not occur because children struggle to shift between dimensions, but rather because they are unable to predict which dimension will be used. These effects of predictability are related to individual differences in children's EFs. Taken together, these findings suggest that EFs may be more broadly involved when children comprehend language, even in instances that do not require conflict resolution.

Introduction

Children, like adults, incrementally process speech, predicting the outcome of a sentence before the last words are uttered. They do so by exploiting cues ranging from coarticulation to syntactic information to real-world knowledge (Borovsky & Creel, 2014; Borovsky et al., 2012; Fernald et al., 2010, 2008; Kidd et al., 2011; Lew-Williams & Fernald, 2007; Lukyanenko & Fisher, 2016; Mahr et al., 2015; Mani & Huettig, 2012, 2014). While incremental processing is ubiquitous, we are most aware of it when our predictions are wrong. This frequently happens in ambiguous sentences that either contain a word with multiple meanings (lexical ambiguity) or a phrase that could have different grammatical roles (syntactic ambiguity). Ambiguity is usually quickly resolved by subsequent information in the sentence, which adults use to revise incorrect predictions (e.g., Spivey et al., 2002).

CONTACT Ron Pomper ron.pomper@wisc.edu Department of Psychology, University of Wisconsin-Madison, 1202 West Johnson Street, Madison, WI 53706, USA

A growing literature suggests that adults' ability to revise incorrect predictions in ambiguous sentences is supported by executive functions (for reviews see Fedorenko, 2014; Mazuka et al., 2009; Novick et al., 2005, 2010; Ye & Zhou, 2009). Executive functions (EFs) involve a constellation of abilities that allow dominant or prepotent behaviors to be overridden in a variety of contexts. While there are many models of EF that include different constellations of abilities, the three most commonly discussed abilities are shifting, inhibition, and updating (e.g., Miyake et al., 2000). Shifting is the ability to flexibly shift between different tasks, operations, or mental sets. Inhibition refers to the ability to overcome responses that are dominant, automatic, or prepotent and attention to irrelevant/distractor stimuli. Updating involves actively manipulating information in working memory. These abilities are dissociable in older children and adults (for review, see Friedman & Miyake, 2017), but may not be in very young children (i.e., 3 years of age; Wiebe et al., 2011).

Individual differences in adults' EFs are associated with their ability to comprehend sentences with syntactic ambiguity, and interventions that improve adults' EFs also improve their ability to revise incorrect predictions while processing such sentences (Novick et al., 2014; Vuong & Martin, 2014). Specifically, adults' ability to resolve syntactic ambiguity is associated with their performance on tests of EFs that assess inhibition (Hussey et al., 2017; Vuong & Martin, 2014). Comprehending ambiguous sentences leads to increased activity in a region of the brain – left inferior frontal gyrus (LIFG) – that is implicated in EFs (Bilenko et al., 2008; Grindrod et al., 2008; January et al., 2009; Klepousniotou et al., 2014; Mason & Just, 2007; Mason et al., 2003; Rodd et al., 2005; Ye & Zhou, 2009; Zempleni et al., 2007). Indeed, adults with lesions to LIFG struggle to revise their incorrect predictions in sentences with lexical or syntactic ambiguity (Bedny et al., 2007; Metzler, 2001; Novick et al., 2009).

EFs are also recruited by other sources of conflict in language comprehension. Individual differences in EFs are associated with adults' comprehension of sentences where a pronoun, adjective, or quantifier can have multiple potential referents (McMillan et al., 2012, 2013; Nozari, Trueswell, & Thompson-Schill, 2016). In situations where conversational partners have different knowledge of their common ground, children and adults' ability to avoid an egocentric bias when comprehending speech is associated with individual differences in EFs (Brown-Schmidt, 2009; Nilsen & Graham, 2009). In language production, EFs support a speaker's ability to choose the right word when there is competition from semantically related items or multiple labels for the same referent (Kan & Thompson-Schill, 2004; Novick et al., 2009; Schnur et al., 2009; Thompson-Schill et al., 1997). What this research has in common is that, in each instance, successful language use requires a decision between multiple, incompatible alternatives. These alternatives create conflict because they are mutually exclusive. EFs help readers and listeners decrease the activation of incorrect alternatives and increase activation of correct alternatives.

Beyond just resolving conflict when language comprehension goes awry, EFs may be engaged by adults' language comprehension more broadly. When bottom-up cues are insufficient to automatically retrieve a word's meaning, comprehension engages EFs (Badre & Wagner, 2002, 2007). Primes that are weakly associated with a target word slow adults' production speed and lead to increased LIFG activation (Martin & Cheng, 2006); this LIFG activation is independent of conflict (i.e., whether retrieval involves two competing interpretations or just one interpretation) and is neurologically distinct from the LIFG activation that results from resolving conflicting interpretations of ambiguous words or sentences (Badre, Poldrack, Paré-Blagoev, Insler & Wagner, 2005; Gold et al., 2006). Adults with LIFG lesions are more affected by prime strength than their neurotypical peers and have impairments in overcoming primed meanings in sentences without conflict (Vuong & Martin, 2015; Wagner et al., 2001). Finally, while adults with LIFG lesions are able to incrementally process speech (e.g., *eat* the cake), their anticipatory fixations are delayed compared to neurotypical adults and adults with more posterior lesions (Nozari et al., 2016). By supporting lexical retrieval, EFs are involved not only when adults comprehend language with conflict, but also language without conflict.

Taken together, this body of research compellingly demonstrates that EFs broadly support language comprehension for adults. Considerably less is known, however, about how EFs support language comprehension during childhood, when both language skills and EFs undergo rapid improvements.

Young children have relatively immature EFs and struggle to revise their incorrect predictions in sentences with lexical or syntactic ambiguity (Anderson et al., 2011; Choi & Trueswell, 2010; Hurewitz et al., 2000; Trueswell et al., 1999; Weighall, 2008). Moreover, children's ability to comprehend sentences with semantic or syntactic ambiguity is associated with individual differences in EFs (Khanna & Boland, 2010; Woodard et al., 2016). There are, however, mixed results regarding which components of EFs are implicated. Both inhibition and updating (shifting was not measured) are associated with children's ability to resolve semantic ambiguity (Khanna & Boland, 2010), while only shifting – and not inhibition or updating – is associated with children's ability to resolve syntactic ambiguity (Woodard et al., 2016).

What remains unclear is how EFs are more broadly involved in children's language processing in the absence of conflict. Past research has shown that children with stronger EFs also score higher on standardized measures of receptive language (Hongwanishkul et al., 2005; Kaushanskaya et al., 2017; Wolfe & Bell, 2004). These standardized measures are designed to assess children's vocabulary size or language comprehension and are *not* limited to ambiguous words or sentences that elicit conflict. While suggestive, these correlations do not identify the specific ways in which EFs are more broadly involved in children's language comprehension.

One way in which EFs may be involved in language comprehension, beyond resolving conflict, is to support children's ability to flexibly shift their focus of attention between different dimensions. Objects have many different properties that can be highlighted through word choice and syntax, and speakers fluidly shift between these properties in speech (e.g., shifting between color and edibility as in "Look at the red apple. Do you want to eat it?"). These shifts occur naturally in much of the previously described research on incremental processing, but their potential impact on language comprehension has been overlooked. In order to comprehend such speech, children must shift their attention between object dimensions such as color and shape. Before 4 years of age, children struggle to switch between these dimensions in a canonical test of EFs – the Dimensional Change Card Sort (DCCS) task (e.g., Zelazo et al., 1996). Such switches between dimensions similarly affect 3-year-olds' language comprehension (Pomper & Saffran, 2016). After identifying a series of objects using one dimension (e.g., color), children are less accurate in identifying a series of objects using a second dimension (e.g., name).

In the current experiment, we expand upon this prior work to examine whether switching dimensions disrupts language comprehension for 5-year-old children. Given the rapid improvements in EFs during early childhood, switches between dimensions may *not* affect 5-year-olds' language comprehension; indeed, by 5 years of age children are able to switch between dimensions in the DCCS (Davidson et al., 2006; Diamond, 2002). Both children and adults' speed in sorting, however, is slowed following a dimensional switch in the DCCS task (Diamond & Kirkham, 2005). We therefore predicted that dimensional switches would disrupt, but not prevent, 5-year-olds' language comprehension (Hypothesis 1). A large literature has demonstrated that adults' responses are slowed when switching between different tasks both because of local costs (shifting between the tasks) and because of global costs (the demands of juggling two different tasks even when there is not a shift; see Kiesel et al., 2010 for a review). These factors are dissociable, activate different regions of the LIFG, and are present in the DCCS (Braver et al., 2003; Diamond & Kirkham, 2005). We therefore predicted that both factors would independently affect children's word recognition accuracy (Hypothesis 2). Finally, past research did not reveal a significant correlation between children's ability to switch between dimensions in a card sort task and a language comprehension task (Pomper & Saffran, 2016). The prior experiment, however, involved younger children and only included one measure of EFs (the DCCS) that was not age appropriate (Akshoomoff et al., 2014). Given the growing body of research demonstrating that EFs support language comprehension for both adults and older children, we predicted that children's ability to switch between dimensions during language comprehension would be associated with individual differences in EFs and that this relation would be specific to shifting component of EFs (Hypothesis 3).

Materials and methods

Participants

The final sample consisted of fifty-six children (35 female) with an average age of 5 years and 6 months (range = 5;0 to 5;11). This was the same sample size as in previous work with similar methods (Pomper & Saffran, 2016). All children were born full term, were reported to have normal hearing and vision,[1] no current ear infections, and were exposed to less than 10 hours per week of a language other than English. Children were recruited from a database of interested families in a mid-sized city in the Midwestern United States. The demographics of the final sample included 52 children who were Caucasian; two who were Caucasian and Asian; and two who were Caucasian, African American, and Asian. Eight additional children were tested but not included in the final sample because they ended the experiment early (n = 4), did not have enough useable data (n = 1), or due to experimental error (n = 3). All parents provided written informed consent and children provided oral assent. The experimental protocols, including the procedures for obtaining informed consent, were approved by the local IRB.

Measures of executive function

Children completed computerized versions of the Dimensional Change Card Sort (DCCS), Flanker, and 1-Back, administered in this same order for all children. These tasks were chosen because they are frequently used to measure different components of EF in children: shifting, inhibition, and updating, respectively. All of the tasks were administered using Python on a Windows 7 laptop connected to a 24-inch external monitor. Children responded by pressing one of two buttons on an RB-844 Cedrus button box. Button caps were modified to match the stimuli for each task.

The exact structure of each task (described below) was piloted and validated in prior research with older children (Kaushanskaya et al., 2017). The tasks were designed to be minimally verbal. Before each task, children received verbal instructions with accompanying visual demonstrations (i.e., images of adults pressing the correct response). Children then completed practice trials with visual feedback (a smiley face for correct, frowning face for incorrect, and stopwatch for no responses), followed by test trials without feedback. For both practice and test trials, there were no verbal instructions. The same pseudorandomized trial order was used for all children in each task.

DCCS

This task was based on Zelazo et al. (2003). On each trial children, were instructed to press the button with the stimulus (a red square or blue circle) that matched a displayed stimulus (blue square or red circle) based on one dimension (color or shape). When sorting by color, the correct response is to press the button with the red square when shown the red circle and to press the button with the blue circle when shown the blue square. When sorting by shape, the correct response is to instead press the button with the blue circle when shown the red circle and to press the button with the red square when shown the blue square. Children completed 4 untimed training trials sorting based on color. They then completed 5 test trials sorting based on color (pre-switch block), 5 test trials sorting based on shape (post-switch block), and 30 test trials where the dimension periodically changed from one dimension to the other (mixed block). In the mixed block, 23 trials required children to sort using the same dimension as the previous trial (same trials) and 7 trials required children to sort using the different dimension from the previous trial (switch trials). As a manipulation check, we compared children's accuracy and latency to respond on trials before and after a dimensional switch. We report the group

[1]None of the children were reported to be color-blind by their parents, though we did not use a standardized test to check for color-blindness. All children, however, were very accurate on Color trials in the looking-while-listening task. Children's mean accuracy in fixating the target image after it was identified by its color (during a critical window 300–1800 ms after the onset of the target word) was 84.9% (SD = 6.5%) and ranged between 68.7% and 99.5%. These data suggest that all children were able to use color to identify the target object.

means and t-test results here; accompanying figures are available in the Supplementary materials. Children were significantly more accurate on pre-switch (M = 92.5%, SD = 8.5%) compared to post-switch (M = 79.6%, SD = 22.7%) trials, $t(55) = 4.17$, $p < .001$. For trials where children responded correctly, their reaction times (RTs) were significantly faster for pre-switch (M = 897 ms, SD = 261 ms) compared to post-switch (M = 1,265 ms, SD = 386 ms) trials, $t(54) = 6.57$, $p < .001$.[2] We found the same pattern of results comparing children's responses on trials where the dimension was the same vs. switched from the preceding trial in the mixed block. Children were significantly more accurate on same (M = 70.8%, SD = 27.3%) compared to switch (M = 58.7%, SD = 13.6%) trials, $t(55) = 3.35$, p = .001. For trials where children responded correctly, their RTs were significantly faster for same (M = 1,548 ms, SD = 649 ms) compared to switch trials (M = 1,644 ms, SD = 699 ms), $t(53) = 2.09$, $p = .04$.

Flanker

In this task, children were instructed to press the button with the left or right arrow that matched the direction of a middle stimulus (a fish facing left or right). The middle stimulus was surrounded by two flanking stimuli on each side. On neutral trials, the flanking stimuli were seaweed. On congruent trials, the flanking stimuli were fish facing the same direction as the middle stimulus. On incongruent trials, the flanking stimuli were fish facing the opposite direction as the middle stimulus. Children first completed 6 untimed training trials. They were then instructed to respond as quickly as possible and completed 6 timed training trials. Finally, children completed 48 test trials (12 neutral, 24 congruent, 12 incongruent). As a manipulation check, we compared children's accuracy and latency to respond on congruent and incongruent trials. We report the group means and t-test results here; accompanying figures are available in the Supplementary materials. Children tended to be more accurate on congruent (M = 93.0%, SD = 9.5%) compared to incongruent (M = 90.2%, SD = 14.0%) trials, $t(55)$ = 1.8, $p = .08$. For trials where children responded correctly, their reaction times (RTs) were significantly faster for congruent (M = 822 ms, SD = 123 ms) compared to incongruent (M = 869 ms, SD = 141 ms) trials, $t(55) = 4.14$, $p < .001$.

1-Back

In this task, children were shown a running sequence of abstract shapes. For each trial (i.e., shape), they were instructed to press the green button if it matched the previous shape and the red button if it did not match the previous shape. The eleven ink-blot shapes that had the lowest nameability values were selected from a normed database (Attneave & Arnoult, 1956; Vanderplas & Garvin, 1959). Children completed 6 timed training trials. They then completed 40 test trials, with 10 trials matching the previous shape and 30 trials not matching the previous shape. Children's accuracy across all trials (i.e., correctly accepting matching trials and rejecting mismatching trials) was 66% (SD = 20.7%); accompanying figures are available in the Supplementary materials. Children did not respond in time, however, for many trials. On average, children responded on 25.7 trials (SD = 9.4) of the maximum of 40. This ranged from only 1 useable trial for one child to all 40 useable trials for two children. On average, 35.7% of trials were missing for the task. Given this much missing data, the 1-Back task did not provide a reliable measure of updating. We therefore excluded this measure from our analyses. Although the trial duration for test trials (1,500 ms) was suitable for older children in prior research, it was not suitable for the younger children in the current experiment. Researchers who plan to use this 1-Back task with 5-year-olds in the future should consider using longer (or untimed) trial durations.

Selecting EF variables

For each task there were multiple trial types and response measures (accuracy and RT). Because of problems with floor and ceiling effects in EF tasks (e.g., Carlson, 2005) and because these tasks were normed with older children (Kaushanskaya et al., 2017), we began by screening the various indexes of

[2]Participants were dropped from statistical analyses involving RTs if they did not respond correctly on any trial in one or more conditions.

performance for each task, excluding the 1-Back. For the DCCS and Flanker, we identified an accuracy index for each task that captured significant variance between children, was approximately normally distributed, and was conceptually relevant (i.e., a change in accuracy due to increased task demands). Past research has found that for children, accuracy indices of EF are more reliable than RT indices (Kaushanskaya et al., 2017). The selected index for the DCCS task was accuracy on trials in the mixed block (both same and switch trials); for the Flanker task, it was the difference in accuracy on Incongruent compared to Congruent trials. Children with better switching skills will score higher on the DCCS, while children with better inhibition will have smaller difference scores on the Flanker.

Measure of language comprehension

Children's ability to shift between dimensions while comprehending speech was assessed using a modified version of a paradigm from Pomper and Saffran (2016). This task uses the looking-while-listening (LWL) method to measure children's lexical processing (Fernald et al., 2008). On each trial, children were shown pictures of two familiar objects, displayed in silence for 2 sec. Children then heard a sentence identifying one of the objects using either its name (e.g., "Find the sock") or its color (e.g., "Find the blue one").

The LWL method is often used with infants and younger children who complete the task without explicit instructions. Indeed, one of the strengths of the method is that motor responses (e.g., pointing to the target image) and verbal responses (e.g., describing the location of the target image) are not necessary; children only need to fixate the target image. Initial piloting, however, revealed that explicit instructions are necessary for 5-year-olds – the task was so simple that many children pointed in an over-exaggerated manner, which interfered with our ability to reliably track their eye-movements. We therefore developed a short introduction with instructions. Before the beginning of the experiment, children were told, "We are going to play a game. It's an easy game. You're going to see two pictures and hear a sentence asking you to find one. Your job is to look at the correct picture." Children were then shown an example trial. They were then told, "For the rest, we're going to play the statue game. In this game, you pretend that you are a statue and you can't move. So, you can only use your eyes to find the correct picture, you cannot point!" Children were then shown an animated image of statues with moving cartoon eyes and were asked if they understood the rules of the game.

There were a total of 32 trials arranged into 3 blocks. In the pre-switch block, there were 8 trials in which the target objects were identified using one dimension. In the post-switch block, there were 8 trials in which the target objects were identified using a second dimension. In the mixed block, there were 16 trials where the dimension periodically alternated between the two dimensions used in the first two blocks. For 8 trials in the mixed block, the target object was identified using the same dimension as the previous trial (mixed-same trials) and for the other 8 trials the target object was identified using a different dimension from the previous trial (mixed-switch trials). Two unique trial orders were created. For each trial order, the assignment of dimension to pre-switch/post-switch (color vs. name), which object was the target/distractor, and trial order (normal vs. flipped) was fully counterbalanced between participants.

Stimuli

Visual and auditory stimuli from Pomper and Saffran (2016) were used in the current study. Pictures of 32 familiar objects were edited using Adobe Photoshop so that the objects matched in size and visual salience. All objects were edited to be monochromatic and one of 8 colors that are familiar to children (blue, orange, red, green, black, yellow, brown, or white). The objects and colors were chosen so that the target words (names and colors) were equally familiar to children.[3] Objects were yoked into

[3]We used the average proportion of 30-month-olds reported to produce each word according to an online database of norms from the MacArthur-Bates Communicative Development Inventories (wordbank.standford.edu), which is the oldest age available. A table with all familiar items, their norms, and yoked pairings is included online at: https://osf.io/vrdm3/.

pairs such that the onsets of both objects' labels and colors were phonologically distinct. Speech stimuli consisted of a carrier phrase with the target word in the final position (e.g., "Find the sock!") followed by an attention-holding phrase (e.g., "Check that out"). A female native speaker recorded multiple versions of each sentence. Tokens were selected to match intonation contour and were edited using Praat so that they were the same intensity (65 dB), all carrier phrases were the same duration, and all target words were the same duration.

Data collection, coding, and cleaning

Children's fixations were tracked using a combination of automatic eyetracking and manual coding. Children were seated approximately 2 feet away from a 55-inch TV and 60 centimeters away from a Tobii X2–60 eye tracker that was mounted on a mechanical arm under the TV. A video camera was also mounted below the TV. Children either sat in their caregiver's lap or on their own with their caregiver standing behind them. All caregivers wore opaque sunglasses to prevent them from seeing the visual stimuli. Additionally, caregivers were instructed to help keep children centered and seated in front of the eye tracker and to remind their child not to point during the task. Before the start of the experimental task, children completed a 5-point calibration, which involved looming circles with accompanying sounds. If calibration was poor (i.e., no calibration or splayed calibration for 3 or more points), the experimenter re-ran calibration.

For our analyses, we quantified children's fixations to the target vs. distractor object during a critical window 300 to 1800 ms after the onset of the target word. This window was based on prior research (Fernald et al., 2008). Before analyzing the Tobii data, we first excluded trials with too much missing data; these were trials in which children did not look at either picture for more than half of the critical window. We then identified children with too much missing data (i.e., 2 or fewer useable trials in one or more conditions). For these children, their fixations were hand-coded offline by trained coders who indicated for each frame (i.e., every 33 ms) whether children were looking at the left picture, right picture, or neither picture (Fernald et al., 2008). Coders used custom software and were blind to the target object, target location, and condition. To determine reliability, 20% of the coded videos (i.e., 3 children) were randomly selected and independently coded by a different coder. Coders agreed on fixation location on 98.6% of all frames and agreed on the timing of shifts in fixations (within 1 frame) 96.2% of the time. The Tobii data, which was recorded at 60 Hz (every 16 ms), was downsampled by binning every 33 ms and averaging. The Tobii and hand-coded data were combined to form the full data set. After including the hand-coded data, only 1 child still had too much missing data and was therefore excluded.

Statistical analyses

We used mixed-effects growth curve analysis (GCA) to quantify changes in the time course of children's fixations as our measure of language comprehension (Mirman, 2014). The dependent variable was the proportion of trials on which children were fixating the target object out of the trials they were fixating the distractor object for each time bin. This proportion was transformed into empirical log-odds to accommodate the binary nature of the data. The empirical log-odds were weighted following Barr (2008). We used the following orthogonal polynomials to quantify changes in the time course of fixations: intercept, linear, quadratic, and cubic time. These time terms quantify different aspects of children's word recognition accuracy. The intercept quantifies the total area under the curve with more positive values indicating a higher average accuracy across the entire window. Linear time quantifies the slope of the line with more positive values indicating a higher average increase in accuracy every 33 ms. Quadratic time quantifies the change in the slope over time with more negative values indicating steeper initial increases in accuracy that declines every 33 ms. Cubic time quantifies the change in the slope of the line around the tails; in the context of the current experiment (i.e., negative quadratic), more negative values indicate a greater asymptote at the beginning of the window, while more positive values indicate a greater asymptote at the end of the window.

A disruption in lexical access would be captured by significant differences between conditions in the cubic (i.e., delayed increase in accuracy), quadratic (i.e., slower increase in accuracy), and intercept (i.e., lower average accuracy) time terms. If switching dimensions does not prevent lexical access (i.e., children ultimately attain the same level of accuracy in fixating the target object), linear time will not differ between conditions.

We fit three models to examine whether there are multiple, dissociable factors that affect children's ability to shift between dimensions when comprehending language. For each model, the within-subject effect of Condition represents a different contrast. Model 1 compares the time course of children's fixations before and after a change in dimensions (contrast coded as −0.5 for pre-switch and 0.5 for post-switch trials). Model 2 examines the effect a change in dimension has on children's fixations in the mixed block when there was no longer predictability in which dimension was used (contrast coded as −0.5 for mixed-same and 0.5 for mixed-switch trials). Model 3 examines the effect of predictability by comparing children's fixations when there was no change in dimension from the previous trial and this was or was not predictable (contrast coded as −0.5 for pre-switch and 0.5 for mixed-same trials).

For each model, we regressed the empirical-log odds of fixating the target on the time terms, the within-subject effect of Condition, the between-subject effect of switching (DCCS) and the between-subject effect of inhibition (Flanker). The between-subject measures were mean-centered. For each fixed effect (Condition, DCCS, and Flanker), we included all 2-way interactions with each time term; we also included the 3-way interactions involving Condition by DCCS and Condition by Flanker with each time term. If individual differences in children's EFs support their ability to shift between dimensions when comprehending speech and this relation is specific to *shifting*, then significant effects of Condition on the time terms should be moderated by children's DCCS, but not Flanker, scores.

We included the full random effects structures for all models, following Barr et al.'s (2013) recommendation. All analyses were carried out in RStudio (version 1.2.5001) using the lme4 package (version 1.1–21). Models were fit using Maximum Likelihood estimation. Because it is computationally and theoretically difficult to estimate the degrees of freedom in mixed-effects models, we analyzed t-scores by assuming a Gaussian distribution; therefore, t-values > 1.96 were considered significant (Mirman, 2014).

Stimuli, an example trial order, data, and analysis scripts are available online at: https://osf.io/vrdm3/.

Results

Effect of a dimensional switch on language comprehension

First, we compared children's accuracy in fixating the target object both before (pre-switch trials) and after (post-switch trials) the dimensional switch. We predicted that the dimensional switch would disrupt children's language comprehension (Hypothesis 1) and that this disruption would be smaller for children with stronger compared to weaker EFs in shifting (Hypothesis 3). The time course of changes in children's accuracy for each Condition are plotted in Figure 1 (for the full table of model results and additional plots see Supplementary Materials). Children's fixations to the target object during the critical window were significantly greater than chance [intercept $b = 1.54$, $t > 38.7$, $p < .001$], increased throughout the window [linear time $b = 3.43$, $t > 12.1$, $p < .001$], and reached a peak asymptote and began to decline at the end of the window [quadratic time $b = -1.44$, $t < -7.7$, $p < .001$]. Children's accuracy in fixating the target object was significantly lower on trials in the post-switch block than trials in the pre-switch block [intercept $b = -0.23$, $t = -2.4$, $p = .02$]. There was not a significant effect of Condition on the remaining time terms [p's > 0.14], indicating that in both blocks, children attained the same level of accuracy at the end of the critical window (linear), and had similar peaks in accuracy (quadratic) that were maintained at the end of the window (cubic). These

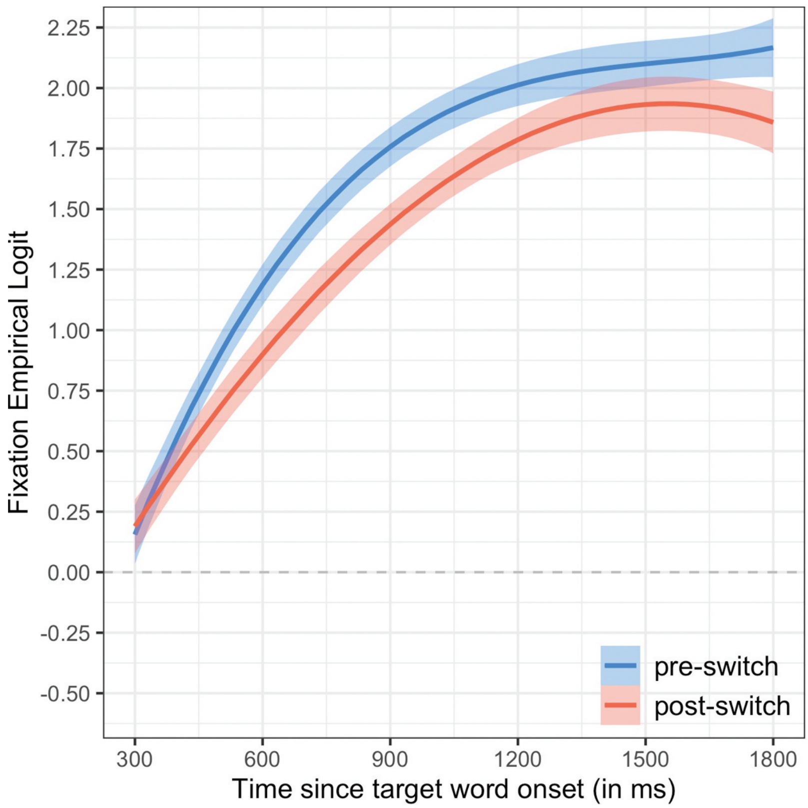

Figure 1. Time course of children's fixations to the target object before (pre-switch; in blue) and after (post-switch; in red) a switch in dimensions in the language comprehension task. The lines are the growth curve model fits for a child with an average DCCS and Flanker score. The ribbons around the lines represent ± 1 SE. The dashed horizontal line at 0 is chance (i.e., equal likelihood of fixating to the target and the distractor object).

results are consistent with our first hypothesis that a dimensional switch would disrupt, but not prevent language comprehension. There was not a significant effect of DCCS or Flanker on any of the time terms [p's > .10]. Nor was the effect of Condition on any of the time terms significantly moderated by individual differences in children's performance on the DCCS or Flanker [p's > .054]. Contrary to our third hypothesis, children's ability to shift between dimensions in language comprehension was not associated with individual differences in their EFs.

Local effect of a dimensional switch on language comprehension

Next, we compared children's accuracy in fixating the target object when it was identified using the same dimension as the previous trial (mixed-same) versus a different dimension from the previous trial (mixed-switch) in the mixed block. We predicted that the dimensional switch would disrupt children's language comprehension due to both local and global costs (Hypothesis 2) and that this disruption would be smaller for children with stronger compared to weaker EFs in shifting (Hypothesis 3). The time course of changes in children's accuracy for each Condition in the Mixed block are plotted in Figure 2. There was a significant effect of Condition on quadratic time [$b = 0.79$, $p = .03$], but *not* on any of the other time terms [p's > 0.28]. Children's overall accuracy in fixating the target object was the same before and after a change in dimensions during the mixed block, although there was a shallower peak in their accuracy following a dimensional change [$b = -1.34$] compared to before the dimensional change [$b = -2.13$]. These results provide mixed evidence in support of

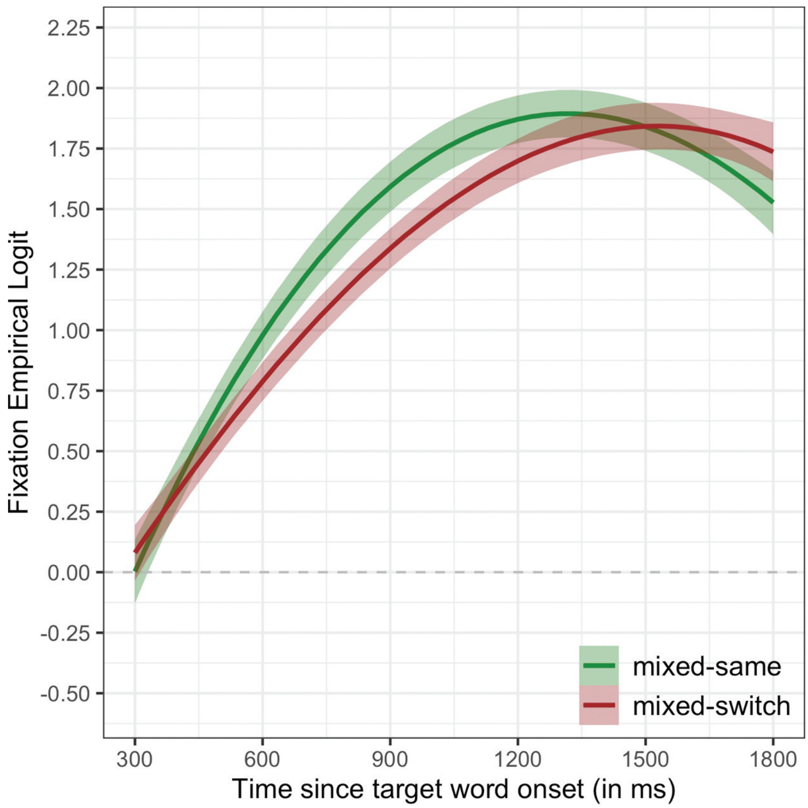

Figure 2. Time course of children's fixations to the target object in the mixed block on trials where the dimension remained the same as the previous trial (mixed-same; in green) and trials where the dimension switched from the previous trial (mixed-switch; in brown). The lines are the growth curve model fits for a child with an average DCCS and Flanker score. The ribbons around the lines represent ± 1 SE. The dashed horizontal line at 0 is chance (i.e., equal likelihood of fixating to the target and the distractor object).

our second hypothesis that a dimensional switch disrupts language comprehension due to local costs. With one exception, there was a *not* a significant effect of DCCS or Flanker on any of the time terms [p's > .14]. Nor was the effect of Condition on any of the time terms moderated by individual differences in DCCS or Flanker [p's > .12]. There was a significant effect of Flanker on linear time [$b = 3.2$, $t = 2.3$, $p = .02$]. Collapsing across trials in the mixed block, children with weaker inhibition (e.g., difference score 1 SD above average), had a greater average increase in accuracy from the beginning to the end of the critical window [$b = 3.76$] compared to children with stronger inhibition [$b = 2.62$]. This effect, however, should be interpreted with caution, because it is likely driven by baseline differences in accuracy at the onset of the critical window. Moreover, we do not find a similar effect in the other models. Therefore, these data appear to contradict our third hypothesis that children's ability to switch between dimensions in language comprehension would be associated with individual differences in their EFs.

Global effect of a dimensional switch on language comprehension

Finally, we compared children's accuracy in fixating the target object when it was identified using the same dimension as the previous trial in the pre-switch block (pre-switch) and the mixed block (mixed-same). We predicted that the dimensional switch would disrupt children's language comprehension due to both local and global costs (Hypothesis 2) and that this disruption would be smaller for children with stronger compared to weaker EFs in shifting (Hypothesis 3). The time course of changes in children's

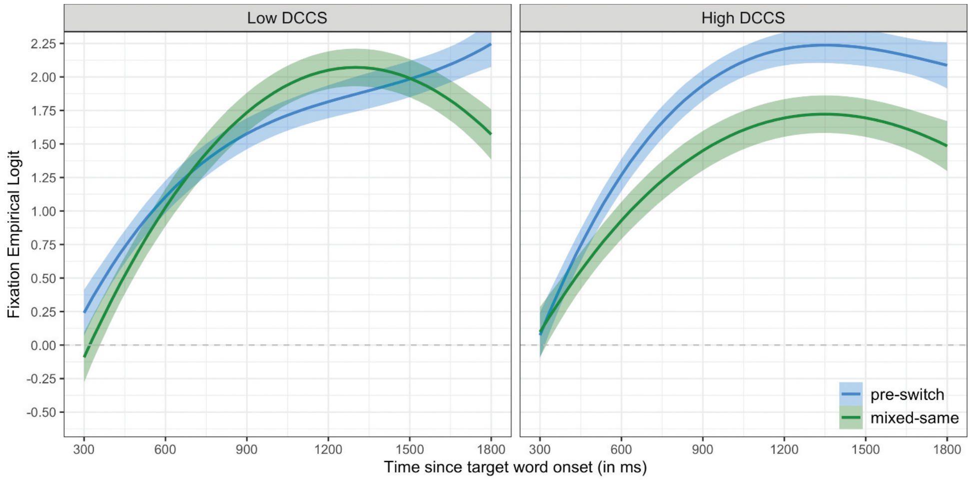

Figure 3. Time course of children's fixations to the target object on trials where the dimension was the same as the previous trial in the pre-switch block (pre-switch; in blue) and in the mixed block (mixed-same; in green). The lines are the growth curve model fits for a child with an average Flanker score and DCCS score 1 SD below average (left panel) or 1 SD above average (right panel). The ribbons around the lines represent ± 1 SE. The dashed horizontal line at 0 is chance (i.e., equal likelihood of fixating to the target and the distractor object).

accuracy for each Condition are plotted separately for a child with low and high scores on the DCCS in Figure 3. Children's accuracy in fixating the target object was significantly lower on mixed-same trials compared to pre-switch trials [intercept:Condition $b = -0.23$, $t = -2.5$, $p = .01$]. There was not a significant effect of Condition on the remaining time terms [p's > 0.13]. This is the *same* pattern of results we observed when comparing children's accuracy before and after a dimensional switch (pre-switch vs. post-switch) in our first set of analyses. These results support our second hypothesis that a dimensional switch affects language comprehension through global costs, by removing the ability to predict which dimension will be used. This effect of predictability on children's word recognition accuracy was significantly moderated by children's performance on the DCCS [intercept:Condition: DCCS $b = -1.13$, $t = -2.2$, $p = .03$; quadratic:Condition:DCCS $b = 5.60$, $t = 2.8$, $p = .01$]. There was not a significant effect of DCCS [p's > 0.41] or Flanker [p's >0.19] on any of the remaining time terms. Children with stronger shifting skills (i.e., DCCS accuracy 1 SD above average), experienced a greater overall decrease in accuracy [intercept:Condition $b = -0.43$] on mixed-same compared to pre-switch trials, compared to children with weaker switching skills [intercept:Condition $b = -0.03$]. Similarly, children with stronger shifting skills had a shallower peak in accuracy on mixed-same compared to pre-switch trials [quadratic:Condition $b = 0.47$], while children with weaker switching skills had a steeper peak accuracy on mixed-same compared to pre-switch trials [quadratic:Condition $b = -1.54$]. Follow-up tests of the simple effects reveal that these EF differences are driven by changes in children's accuracy on predictable, but *not* unpredictable trials. On trials in the pre-switch block, there was a marginally significant effect of DCCS on children's overall accuracy [intercept:DCCS $b = 0.57$, $t = 1.74$, $p = .08$] and a significant effect of DCCS on children's peak in accuracy[quadratic:DCCS $b = -3.32$, $t = -2.43$, $p = .02$]. On trials in the mixed block, however, children's performance on the DCCS was *not* related to their word recognition accuracy [p's > 0.13]. Taken together, these results suggest that individual differences in children's EFs do *not* predict how well they can switch between dimensions (our third hypothesis), but rather how strongly they anticipate a specific dimension used when comprehending language.

Discussion

We used a looking-while-listening paradigm to assess children's ability to flexibly shift their attention between dimensions during language comprehension. On each trial, 5-year-olds saw pictures of two familiar objects and heard a sentence identifying the target object. We found that after a series of trials in which objects were identified using one dimension (e.g., their colors), children were significantly less accurate in fixating correct objects that were identified using a second dimension (e.g., their names). This cost in switching directly replicates prior research, which found the same effect for younger children (Pomper & Saffran, 2016). Considering that a somewhat analogous effect has been observed with adults (Heller & Chambers, 2014), it is likely that we would find the same cost in switching if we were to test even older children with our paradigm, suggesting developmental continuity in this task. Difficulty in flexibly shifting attention between dimensions when comprehending speech is thus not limited to young children who have relatively immature EFs.

This difficulty in language comprehension following a dimensional switch can result from multiple factors. A key factor appears to be changes in predictability – the degree to which children are able to anticipate what dimension will be used to identify an object beforehand. This is supported by two results from the current study. First, although the time course of children's word recognition accuracy was different before and after a dimensional switch in the mixed block, children's overall accuracy was unaffected. Thus, when children were no longer able to anticipate which dimension would be used (because there is no longer consistency between trials in the mixed block), their overall accuracy in word recognition was the same regardless of whether the target object was identified using the same or a different dimension from the previous trial. Second, we found that children's word recognition accuracy was affected by changes in predictability, even on trials where there is not a dimensional change. Children's word recognition accuracy was lower on trials without a dimensional change in the mixed block compared to trials without a dimensional change in the pre-switch block.

The finding that children had equivalent accuracy both before and after a dimensional switch in the mixed block is somewhat surprising given that children were affected by an analogous dimensional change in the DCCS task where children were faster and more accurate on trials in the mixed block of the DCCS when the dimension was the same as the previous trial than when the dimension switched. This pattern of results suggests that, despite superficial similarities, there are fundamental differences between our language comprehension and DCCS tasks. We return to this issue below.

Finally, we found that individual differences in children's EFs predicted the extent to which their word recognition accuracy was affected by changes in predictability. Children with stronger shifting skills (measured using the DCCS) experienced a greater boost in word recognition accuracy when the dimension used to label the target object was predictable compared to unpredictable. It may seem counter-intuitive that children's performance on the mixed block of the DCCS is correlated with their word recognition accuracy on pre-switch, but not mixed-same trials in our looking-while-listening task. We believe, however, that this pattern of associations is due to two important methodological differences between the tasks. In the DCCS task, the different dimensions yield conflicting responses (e.g., matching the blue square with either the red square or the blue circle) and children are prompted with the relevant dimension *before* the trial starts. In our language comprehension task, however, the different dimensions do not yield conflicting responses (e.g., identifying an object using either its name or color) and children are not prompted with the relevant dimension beforehand. Children who are more successful on the DCCS are better able to focus their attention on one dimension and ignore the second dimension (e.g., Benitez, Vales, Hanania, & Smith, 2017). These same children benefit the most on precisely those trials in our language comprehension task where they are able to focus their attention on one dimension (pre-switch trials), because they can anticipate which dimension will be used.

This is a novel finding that suggests a new way in which EFs may support language comprehension: children with stronger EFs may benefit *more* from regularities in the input, because they are better able to focus their attention on a specific dimension. This is a significant expansion in the role of EFs in language comprehension. Previous research has demonstrated that EFs support language comprehension only under specific circumstances – when children and adults must resolve conflicting interpretations of ambiguous words or sentences. It is unclear, however, how often children and adults encounter truly ambiguous words or sentences that elicit such conflict. Ambiguous words are generally used in contexts that strongly favor one meaning (Piantadosi et al., 2012). The types of sentences that create syntactic ambiguity may be infrequent in natural conversation (Roland et al., 2007). Moreover, this ambiguity is often eliminated with additional linguistic information (e.g., "Put the apple *that's* on the towel in the box") or visual information (e.g., the presence of two apples, which necessitates the use of a modifier; Spivey et al., 2002). The results from the current experiment, however, suggest that EFs may support language comprehension more broadly, not just in situations that require the resolution of conflict.

Potential mechanisms

Given the correlational nature of our results, it is important to be cautious in positing a causal effect of EFs on language comprehension. If there is a causal relation, it may be in the opposite direction or even bi-directional. In this section, we highlight previous research that suggests potential mechanisms by which language and EFs may mutually support one another throughout development.

One possibility is that increases in children's ability to control their attention lead to improvements in language development. As described in the Introduction, interventions that improve adults' EFs also improve their comprehension of ambiguous sentences, and individual differences in children's EFs are correlated with their comprehension of ambiguous sentences (Khanna & Boland, 2010; Novick et al., 2014; Woodard et al., 2016). On this view, stronger EFs improve comprehension of ambiguous sentences by boosting children and adults' ability to inhibit incorrect, conflicting interpretations. In the current experiment, stronger EFs may improve children's comprehension of unambiguous sentences by boosting their ability to focus their attention on relevant (e.g., color), rather than irrelevant, attributes of the target object. Naming objects improves the speed with which 3-year-olds find targets in a visual search task (Vales & Smith, 2015). This facilitation may occur because the label biases children to attend to more relevant information about the target (e.g., its shape; Landau et al., 1998). Our measure of language comprehension is methodologically similar to a visual search task with fewer items. It is possible that the consistent block of trials improved children's ability to fixate the target object by biasing their attention to the more relevant information. Children who are better able to focus their attention (i.e., stronger EFs) may benefit more from this consistency.

It is also possible that improvements in children's language ability lead to increases in children's ability to control their attention. This idea is featured prominently in Vygotsky's theory that children use private speech (which eventually becomes internalized speech) to organize and regulate their behaviors (1934/1962, see also Cragg & Nation, 2010). Explicitly teaching children to use labels improves performance on tasks measuring proactive cognitive control for younger (4- to 5-year-olds), but not older children (7- to 10-year-olds; Doebel et al., 2018; Kray et al., 2015). Three-year-olds' performance on the DCCS is improved by labeling (Kirkham et al., 2003). Moreover, verbal suppression interferes with adults' ability to switch between tasks and age-related improvements in task-switching are reduced when children are encouraged to verbalize (Emerson & Miyake, 2003; Kray et al., 2008). Together, these results suggest that age-related improvements in children's ability to control their attention are attributed at least in part to improvements in their ability to use language to focus their attention. Indeed, some longitudinal research suggests that early individual differences in language skills predict long-term improvements in EFs, but not vice versa (Gangopadhyay et al., 2019; Schneider et al., 2005).

Limitations and future directions

While suggestive, the current results are only a first step in examining how shifts between dimensions affect children's language comprehension. The generalizability of these findings is limited by several methodological issues, which can be addressed by future research. First, it is important to determine whether the correlation we observed between children's language comprehension and EFs generalizes to other tasks. Of our measures of EFs, the DCCS shared the most features with our language comprehension task. We cannot rule out the possibility that the observed correlation reflects shared task demands rather than an association between children's EFs and language comprehension. This limitation could be addressed in future research by using additional measures of EFs. As previously discussed, children's EFs may improve language comprehension by boosting their ability to proactively focus their attention on the dimension that will be used. Future research could include tasks like the AX-CPT that have been adapted to measure proactive vs. reactive cognitive control in children (e.g., Lucenet & Blaye, 2014) or tasks that measure children's ability to simultaneously attend to multiple dimensions (e.g., Podjarny et al., 2017). Second, it is important to understand how shifts between different types of dimensions affect language comprehension. In the current experiment, we focused on the two dimensions that are most frequently used in the DCCS – names and colors. These two dimensions, however, differ in many ways. The objects in the current experiment did not have stereotypical colors, so objects' names, but not colors, were integral to their identity. Names and colors also belong to different grammatical categories (nouns and adjectives, respectively). It is important for future research to address whether shifts between other dimensions similarly disrupt language comprehension. Third, changes in predictability were confounded with trial order in the current experiment, because trials in the pre-switch block always occurred before trials in the mixed block. Thus, children's word recognition accuracy may also have decreased as a result of fatigue. These factors can be teased apart by future research that conceptually replicates the effect of dimension predictability on language comprehension (see below). Finally, given the correlational nature of our results, it is important to be cautious in positing causal directions between EFs and language comprehension. Future research involving interventions that improve EFs can more directly test whether the effect of predictability on language comprehension is moderated by individual differences in EFs (e.g., Hussey et al., 2017).

The potential effects of dimension predictability on language comprehension in the current experiment raise interesting questions for future research. As described in the Introduction, children use a variety of cues to incrementally process speech. In all of these experiments, however, children are using these cues to anticipate a specific referent before it is named. For instance, when children hear the sentence "Eat the cookie," they will start fixating the cookie before it is even named. In many instances, however, specific words or referents may not be predictable, but categories or classes of words are (Federmeier & Kutas, 1999; Federmeier et al., 2007; Schwanenflugel & LaCount, 1988; Schwanenflugel & Shoben, 1985). Children may use the preceding context to not only anticipate the target object, but other information as well. Research on structural priming demonstrates that in both production and comprehension, abstract grammatical categories can be primed independent of specific referents (e.g., Bock, 1986; Bock et al., 1992; Huttenlocher et al., 2004; Mehler & Carey, 1967; Savage et al., 2003, p. 2006). In most research, including the current experiment, children's language comprehension is assessed using individual sentences (e.g., "Find the red one"). The results from the current experiment suggest that children may be using the preceding trials to anticipate which dimension will be used to identify a target object. Natural language use, however, does not consist of independent sentences. Children may therefore be able to use preceding sentences (e.g., "Look at these beautiful colors") to more accurately anticipate what dimension will be used to identify a target object. While such predictions will not allow children to fixate an object before it is named, they may improve children's word recognition accuracy. This is an important question for future research to explore.

Conclusions

Much of the research literature demonstrating correlational and causal relations between EFs and language comprehension has focused on situations involving conflict. Children and adults with stronger EFs are better able to select between competing interpretations of ambiguous words or sentences. In comprehending language, however, there are other sources of ambiguity that do not involve conflict. For instance, a speaker can identify an object using many different dimensions –

using its name, color, size, superordinate category membership, or even associated actions. These alternatives are not incompatible or in conflict – an apple is both red and edible. Nevertheless, the current data suggest that ambiguity in which dimension will be used to identify an object disrupts children's language comprehension and the size of this disruption is mediated by individual differences in children's EFs. The current experiment demonstrates that EFs may be more broadly involved in comprehending language. Even in instances where comprehension does not go awry, children's ability to focus and shift their attention affects their ability to comprehend speech.

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ORCID

Ron Pomper http://orcid.org/0000-0001-5595-4192

Data Availability

All stimuli, data, and analysis scripts are available online at: https://osf.io/vrdm3/

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