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Dimensional Label Learning Predicts the Developmental Status of Executive Function

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Abstract

The Dimensional Change Card Sort Task (DCCS) is a measure of the developmental status of early childhood EF. In this task, children use verbal rules regarding the features and dimensions of objects to sort cards by shape or color. A recent dynamic neural field model explains development in the DCCS task based on the strength of associations between labels and visual features. In this project, we explored the role of dimensional label learning (DLL) in the development of flexibility in the DCCS task. Three- and 4-year-olds were given DLL tasks along with the DCCS task. We measured hemodynamic activity as children performed these tasks using fNIRS. Results showed that color label production produced activation throughout frontal and left temporal areas. Importantly, hemodynamic activation during the DLL tasks predicted performance in the DCCS. These results suggest that the neural systems involved in DLL influences children's ability to flexibly switch between rules.

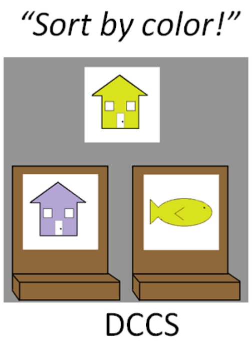
Keywords: executive function; dimensional labels; fNIRS

Executive Function Development

Executive functioning (EF) is a term used to refer to higher-level aspects of cognition such as inhibition, working memory, and flexibility (Miyake et al., 2000; Buss, Wifall, Hazeltine, & Spencer, 2014). EF undergoes rapid changes in the preschool years and continues to develop on into adolescence and early adulthood. (Best & Miller, 2010; Blair, Zelazo, & Greenberg, 2005; Huizinga, Dolan, & van der Molen, 2006). Measures of EF in early childhood are predictive of later physical health, substance dependency, personal finances, as well as criminal offending outcomes (Moffitt et al., 2011). Thus, improving EF during early childhood could facilitate diverse improvements in developmental outcomes. Designing effective interventions for EF development, however, will require understanding its underlying processes. There is little consensus regarding the mechanisms or processes that give rise to EF (Happaney & Zelazo, 2003; Kirkham & Diamond, 2003; Munakata, Morton, & Yerys, 2003). Various attempts have been made to improve EF by targeting specific executive functions such as working memory or inhibition. However, such efforts typically fail to produce gains outside of the trained task or generalizability to other functions (Diamond & Lee, 2011). These findings suggest that our current understanding of EF is limited.

Dimensional Change Card Sort (DCCS) Task

One task that has been the focus of many theories of EF development is the Dimensional Change Card Sort (DCCS) task. In the standard version of this task, target cards are affixed to the trays where children sort to show which features go where for the different sorting rules. The test cards that children sort match either target along different dimensions. Children are asked to first sort either by 'color' or 'shape' in the pre-switch phase. After a series of trials, children are then asked to switch and sort by the other dimension. Three-year-olds tend to perseverate and continue sorting by the pre-switch rule whereas 5-year-olds have little difficulty applying the new post-switch rule.



The DCCS imposes multiple processing demands. Children must maintain an active representation of the relevant feature dimension, inhibit processing of the irrelevant dimension, and update these processes when the rules change. Previous theories have focused on the development of individual components of EF such as inhibition (Rennie, Bull, & Diamond, 2004; Kirkham, Cruess, & Diamond, 2003) or have centered on abstract representational processes that are localized to frontal cortex and operate in a top-down manner on information processing (Morton, & Munakata, 2002; Zelazo et al., 2003). No explanation so far has managed to integrate lower level perceptual processes into EF development or even determine how learning might affect EF.

Label Learning as a Developmental Mechanism

A recently proposed dynamic neural field model shifts away from this focus on EF components and instead focuses on the underlying processes that give rise to EF. The DCCS requires using verbal rules to sort cards. However, no previous research has examined children's comprehension and production of labels for features and dimensions in relation to children's ability to follow rules. A neurocomputational model proposed by Buss and Spencer (2014) suggests that children use label representations to enhance processing of task-relevant visual features. This model has successfully explained performance and development in the DCCS task across a wide array of effects.

In the model, learning labels for visual features creates structure in the connectivity between frontal and posterior regions. Activation of labels, such as "shape" or "color" enhances processing of specific, task-relevant dimensions. Labels and features are coupled reciprocally such that labels can lead to activation of features, and the activation of features can result in the activation of labels. This model binds features to spatial locations when making decisions. The pattern of decisions made during the pre-switch phase causes the accumulation of memory traces, and these memory traces create a bias during the post-switch phase to continue sorting by the pre-switch dimension.

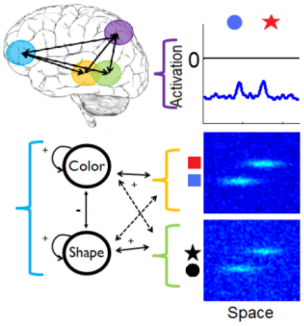


Figure 2: DNF Model

Dimensional Label Learning

Previous research has demonstrated that mastering dimensional labels such as "color" involves a system of mappings, not simply associating a label ('red') to an object property in the environment (Sandhofer & Smith, 1999). Children first learn that 'color' is related to other labels for colors such as 'blue' or 'red' (termed word-word mappings). Next, children demonstrate an understanding that the label 'blue' refers to the blue color of an object (word-property mapping). More difficult still is understanding that two objects can share the same color, such as a blue cup and a blue box (property-property mapping). The final mapping involves the connection from the overall category of color to a related color label ('blue') to a blue object (word-word-property mapping).

Previous research has developed tasks to assess the order of acquisition of these color mappings (Sandhofer & Smith, 1999). The production task involves asking children "What color is this?" and targets word-word mappings (understanding that the category of color involves a series of color labels, such as blue). When answered correctly, this task also demonstrates an understanding of property-word mappings, but this tends to be more difficult for children. The comprehension task involves presenting children with an array of objects and asking "Which one is blue?" and assesses word-property mappings (understanding that the label blue applies to the 'blueness' of an object). Finally, the comparison or matching task involves presenting children with two objects that are similar along a dimension and asking them to find another object that shares that feature out of an array of other options. This task assesses property-property mappings (understanding that similar and dissimilar objects can share the same color).

Interestingly, children often have the most difficulty with these property-property mappings, even if they can reliably and accurately name colors in the production and comprehension tasks. While it may seem that children need the ability to abstract the color of objects before they can learn color labels, Sandhofer and Smith (1999) proposed that success in the matching task actually depends on first learning other color labels. Therefore, this type of label learning typically occurs later on, after comprehension and production. Sandhofer and Smith suggested that this difficulty involves selective attention, as children must first learn a number of color labels that guide their attention to the dimension of color in objects, allowing them to match later. However, no research has yet assessed whether or how dimensional label learning influences attentional processes.

Typically, children are proficient in their color labels before they are able to perform the DCCS task. However, the neural activation dynamics involved in performance on this DLL may provide a window into the status of children's dimensional label knowledge that might be predictive of their performance on the DCCS task. In the study below, we assess neural activation while children performed the DLL tasks from Sandhofer and Smith (1999) and examined whether neural activation during these tasks was associated with their performance on the DCCS task

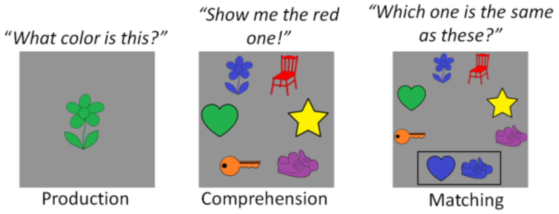


Figure 3: DLL Tasks.

The influences of labels have been examined in the context of the DCCS in different ways. Some have found that providing dimensional labels can support switching (Doebel, & Zelazo, 2013). For example, Kirkham, Cruess, and Diamond (2003) found that asking 3-year-olds to label the relevant dimension when sorting facilitated successful post-switch performance, but this was not replicated in another study (Müller, Zelazo, Lurye, & Liebermann, 2008). Other research has found that children were able to switch rules more successfully if they were given uninformative labels, such as labeling the DCCS generically as a sorting game instead of a shape or color game, during the pre-switch phase but informative labels during the post-switch phase (Yerys, & Munakata, 2006). However, no previous studies have examined the status of children's comprehension and production of labels in relation to DCCS performance.

Examining Associations Between Dimensional Label Learning and DCCS Performance

We administered the DLL tasks from Sandhofer and Smith (1999) and the DCCS task to a group of 3- and 4-year-olds while measuring fNIRS data from bilateral frontal, left temporal, and right parietal regions. We focused on these regions because they have been previously implicated as important to successful performance on the DCCS task (Buss & Spencer, in press). In general, lateral frontal is thought to be a language region. In addition, temporal and parietal areas have been implicated as being important for object representation (Martin, 2007).

Our research aims to address two questions. First, what cortical regions are involved with successful performance on the DLL tasks? Second, is activation during DLL related to children's performance on the DCCS task? We expect 3- and 4-year-olds to be proficient with color labels. However, neural activation during the DLL tasks could reflect differences in the quality of learning that underlies their performance on DLL tasks. To the extent that DLL is related to children's dimensional attention skills, we expect activation during DLL tasks to be predictive of children's performance on the DCCS task.

Participants

This project included a sample of 37 children recruited from the Knoxville community. Seven children were excluded for failing to complete all tasks, and eight children were excluded for motion artifacts after fNIRS analysis, leaving a total sample of 22 participants (eight 3-year-olds, *M* age=42.6 months, 5 males, 3 females; thirteen 4-year-olds, *M* age=50.1 months, 6 males, 7 females). One participant withheld demographic information.

Procedure

Children completed the DCCS task along with the production, comprehension, and comparison tasks for colors that were used by Sandhofer and Smith (1999). While studying shape labels would also be of interest, only color tasks were used to keep each testing session to a reasonable length (Verdine, Lucca, Golinkoff, Hirsh-Pasek, & Newcombe, 2016). Tasks were administered on a 42" touchscreen monitor that was connected to a PC running E-Prime software. Each of the 3 DLL tasks included 3 blocks of six trials (54 trials total) and used 6 different colors (red, orange, yellow, green, blue, and purple). For the production tasks, children were shown a single object and were asked "What color is this?". The experimenter entered the child's responses into 3 categories based on whether the child responded correctly, incorrectly, or if they refused to give a response or stated they didn't know. For the comprehension tasks, children were shown a circular array of six objects and were asked, for example, "Which one's blue?". Children responded by touching one of the objects on the screen. For the matching task, children were shown two objects that were similar in color and an array of 6 objects that were arranged in a half-circle and were asked, "Do you see how these two are the same? [pointing to the two reference objects] Which one of these is the same like these two? [pointing to the objects along the imaginary half-circle]" The child was then allowed to touch one of the objects to indicate their choice.

For the DCCS, children were first given practice with a physical set of cards, and the pre-switch dimension (shape or color) was counterbalanced between participants. They were told "This is the shape/color game. In the shape/color game, red ones/circles go here [pointing to one target location], and blue ones/stars go here [pointing to other target location]. Where does this one go in the color/shape game [holds up card to sort]?" The children then sorted five practice cards. After, the children completed the task on a touchscreen computer. There were 5 pre-switch trials, 5 post-switch trials, and 30 mixed-block trials in which the sorting rules switched randomly. The first 10 trials used a yellow house and purple fish for the target cards, and the mixed block trials used a green bunny and a red chair. Half of the children completed the DCCS task first and the other half completed the DLL tasks first. Task order for the DLL tasks was randomized.

fNIRS Data Collection and Analyses

Near-infrared spectroscopy (fNIRS) was used to monitor cortical activity by measuring levels of oxygenated (HbO) and deoxygenated (HbR) hemoglobin in the cortical surface while children completed these tasks (Boas & Franceschini, 2009). Data were collected at 25 Hz using a Techen CW6 system with wavelengths of 830 nm and 690 nm. The fNIRS probe was designed with 8 channels of data depicted in Figure 4. Two channels were over bilateral frontal cortex, and two channels were centered on bilateral temporal-parietal cortex.

Using HomER2 software (Huppert, Diamond, Franceschini, & Boas, 2009), the mean baseline was subtracted and data were transformed into an optical density measure. To remove extreme frequencies slower than .016 Hz and faster than 2 Hz, data were band-pass filtered. A low pass filter of 2 Hz was used to preserve high frequency fluctuations that could be due to motion. Next, these motion artifacts were eliminated from each region by removing trials with a change in optical density larger than 0.3 absorbance units within the time-window between 2 seconds before to 12 seconds after the onset of the dimensional cue. Data were then band-pass filtered again to hold only frequencies between .016 and .5 Hz. Concentration data were computed using the known extinction coefficients of oxygenated and deoxygenated hemoglobin and the modified Beer-Lambert Law (Boas et al., 2001).

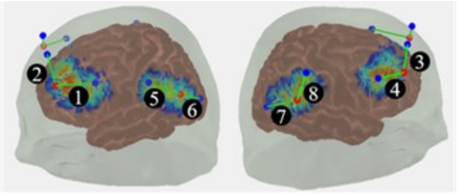


Figure 4: fNIRS Probe Design

Results

Both 3- and 4-year-olds were at ceiling on the DLL tasks, with no differences between ages or between tasks (see Figure 5). Unusually, the DCCS also showed the same pattern, with no differences in accuracy between the 3- and 4-year-olds.

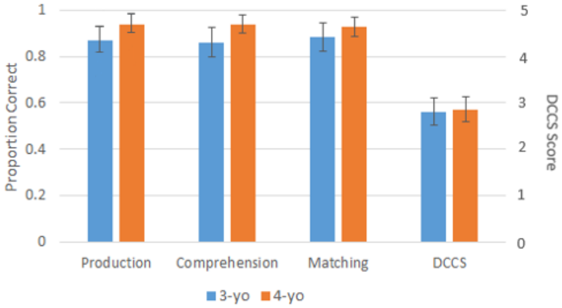


Figure 5: Behavioral Performance.

Table 1: Channel Activation for Production (Oxy-Hb > Deoxy-Hb)		
Channel	***t*-Statistic**	***p***
1	3.799	*.001*
2	2.882	.009
4	2.980	.007
5	2.967	.008
6	2.786	.012

To investigate activation across channels, we ran a series of 3 repeated measures *t*-tests per channel for each DLL task with an adjusted *p*-value of 0.017 (see Table 1). We observed significant activation (HbO greater than HbR) for the production task only in channels 1, 2, 4, 5, and 6 (see Table 1 and Figure 6).

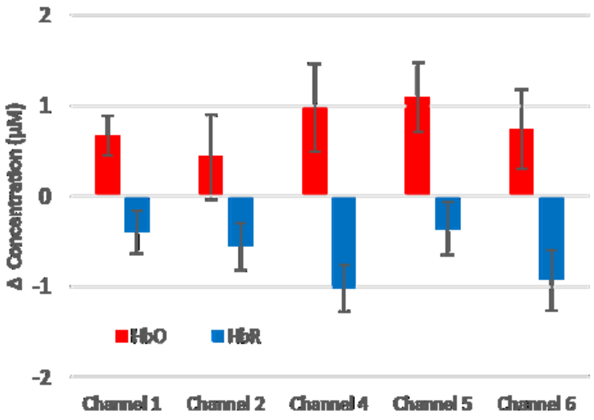


Figure 6: Channel Activation for Production

Table 2: DLL HbO and DCCS Correlations			
Channel	Task	*r*	*p*
2	Comprehension	-.428	.047
3	Matching	.483	.023
4	Matching	.490	.024
7	Production	.587	.007
7	Matching	.575	.008

To assess our hypothesis that DLL activation is related to DCCS performance, we also examined correlations between DLL task HbO levels and DCCS performance (see Table 2). We found a negative correlation in channel 2 indicating that HbO concentration for the comprehension task was inversely related to performance in the DCCS. In channels 2, 3, and 7 the matching task HbO was positively related to DCCS performance. Finally, production HbO was also positively related to DCCS performance. Thus, activation during the DLL tasks varied in a way that was meaningfully related to children's performance on the DCCS task.

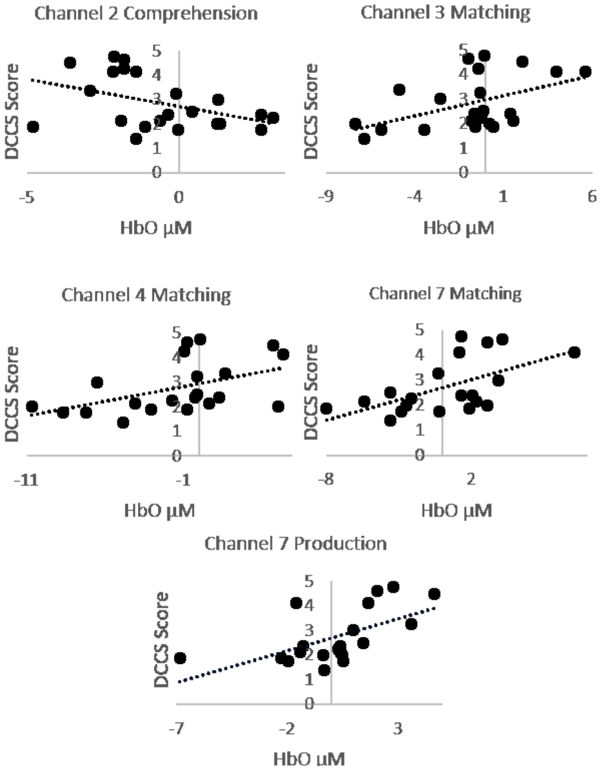


Figure 7: HbO and DCCS Correlations.

Discussion

This study provides the first examination of the relationship between dimensional label learning and performance in the DCCS task. Our study revealed that 3- and 4-year-olds performed very well on the DLL tasks but showed variable performance on the DCCS task, which makes it valuable as a measure of the developmental status of EF. When examining patterns of hemodynamic activation during the DLL tasks, individual variation was meaningfully predictive of performance on the DCCS task. This suggests that although group level activation was not observed in the comprehension or matching tasks, perhaps developmental changes are still emerging in these regions as children refine their representations of these labels.

It is interesting to note that most correlations between hemodynamic activity and DCCS performance were positive, suggesting that stronger engagement of those cortical regions during the DLL tasks was associated with better performance in the DCCS task. However, the correlation between activation in the comprehension task in left frontal cortex was negative. This suggests that learning dimensional labels may involve more than just increasing activation over development. Indeed, this suggests that there may be a more subtle tuning of regions or a functional specialization that involves decreasing activation in lateral frontal cortex during label comprehension.

There are many theories of DCCS performance but none of them address how DLL is involved. For example, the Cognitive Complexity and Control (CCC) theory suggests that successful rule-use arises from consciously representing and reflecting on the complex rules of the task (Frye, Zelazo, & Palfai, 1995). According to this theory, children fail on the DCCS when they cannot represent complex or hierarchical rules. Although CCC theory suggests that rule representation is guided through linguistically mediated reflection on the task, it is not clear how dimensional labels would be involved in this framework. A connectionist model has also been proposed to explain development in the DCCS task. However, this model implements an abstract rule representation system (Morton, & Munakata, 2002). The model could successfully switch in the DCCS when the recurrent connectivity between the prefrontal cortex (PFC) units was strengthened locally. Again, however, this leaves little room for dimensional labels, as DLL requires a variety of posterior brain regions beyond PFC.

The DNF model by Buss and Spencer (2014) provides a new way to explain how DLL influences EF processes. Indeed, this is the first explanation that captures how the neurocognitive dynamics of learning the associations between labels and features might affect EF tasks. Learning dimensional labels recruits activity from frontal and posterior brain regions, and strengthening frontal-posterior connectivity in the model led to switching behavior in the DCCS reflective of 4-year-old children. This implies that DLL could provide a foundation leading to successful DCCS performance. Interestingly, although the children were at ceiling behaviorally for the DLL tasks, neural activation for these tasks was variable, indicating there may be neural changes occurring that weren't reflected in performance on the behavioral task. Very little research has been done on the neural basis of dimensional label learning tasks, and this is one of the first studies to demonstrate that dimensional label learning can impact EF. This indicates that DLL seems to be a promising explanation to pursue for future research in understanding the processes involved in the development of EF.

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