FOUNDATIONAL NUMERICAL SKILLS IN CHILDREN WITH DOWN SYNDROME

by

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ABSTRACT

The Approximate Number System (ANS) is the cognitive system that makes up the intuitive, non-numerical/non-symbolic representation of all numbers. ANS performance in a number acuity task is believed to be an important predictor of numerical skills. It is important to understand how well ANS functions in individuals with Down syndrome (DS) to better understand the role numerical skills play in this special population. If we can better understand how numerical skills function in DS, then we can develop interventions to help improve these numerical skills in individuals with DS and improve their adaptive skills that are limited by numerical skills, such as counting change and cooking. The current study compared both the group with DS and the TD group matched by receptive vocabulary skills on their non-symbolic and symbolic numerical skills by taking the overall scores for the ANS and the overall scores for symbolic numerical skills across receptive vocabulary scores. Results revealed there were no significant main effects nor interaction found when task x group was compared in a 2x2 repeated measures ANOVA. Additionally, results revealed there was no significant difference between groups for both non-symbolic and symbolic numerical skills when measured across PPVT-5 GSV scores. Implications and limitations of the study findings are discussed.

DEDICATION

This thesis is dedicated to everyone who helped me and guided me through the trials and tribulations of creating this manuscript. In particular, my family and close friends who stood by me throughout the time taken to complete this masterpiece.

LIST OF ABBREVIATIONS AND SYMBOLS

DS Down syndrome

TD Typically Developing

MA Mental Age

a Cronbach's index of internal consistency

df Degrees of freedom: number of values free to vary after certain restrictions have been placed on the data

F Fisher's *F* ratio: A ration of two variances

M Mean: the sum of a set of measurements divided by the number of measurements in the set

p Probability associated with the occurrence under the null hypothesis of a value as extreme as or more extreme than the observed value

t Computed value of *t* test

< Less than

= Equal to

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1. INTRODUCTION

Numerical skills are an important cognitive skill found in both humans and nonhumans (e.g. monkeys) (Feigenson et al., 2004). They are a foundational skill needed in everyone's daily lives. Examples of numerical skills used daily include, but are not limited to, counting change, reading a clock, reading numbers (e.g., speed limit signs), measuring ingredients for cooking, and much more. Foundations of numerical skills are proposed to be a core-knowledge system, which means that humans are born into the world with a predisposition to learn basic numerical skills. With the large role numerical skills play in individuals' daily lives and basic numerical skills being a proposed core-knowledge system, it is surprising that there is still so much unknown about the cognitive development of numerical skills, especially in special populations such as individuals with Down syndrome (DS). The current study aims to address this issue and help begin to fill in the gaps that currently exist in the literature on the development of numerical skills in children with DS.

Down syndrome (DS) is a genetic disorder caused by a triplication of the 21st chromosome and often associated with intellectual disability (ID) (Kittler et al., 2008). Individuals with DS are often characterized by their physical characteristics of a flat face, small eyes, and short stature. In addition, there is a distinct cognitive-linguistic phenotype associated with DS, which has become more detailed as a result of research over the last 20 years. This phenotype includes specific deficits and relative strengths in specific aspects of language, memory, and executive function. In language, individuals with DS have deficits in expressive vocabulary, while receptive vocabulary is relatively better (Law & Bishop, 2004); in memory, verbal short-term memory (Hick et al., 2005) and working memory are especially poor, while some aspects of visuo-spatial short-term memory are relatively strong (Baddeley & Jarrold, 2007). In executive function, shifting, inhibition, and working memory are especially poor and emotional control is relatively strong (Rowe et al., 2006). Knowing the cognitive-linguistic phenotype helps parents and educators understand and anticipate everyday struggles experienced by individuals with DS.

We can expect the cognitive-linguistic profile of DS to impact higher skills such as reading and math. Much is already known about aspects of reading skill that are especially poor and relatively strong in DS (Chapman, 1997); however, little is known about aspects of math skills that may be especially poor or relatively strong in this special population. The purpose of the proposed study is to examine two early-developing numerical skills in children with DS – one that might be a relative strength and another that might be considerably more difficult. The potential relative strength to be examined is the ability to judge quantities visually via the "approximate number system" (ANS). The potential weakness is the ability to use symbols (i.e., Arabic numbers) to judge quantity because of the role that verbal skills play in the development of symbolic numerical skills. This is important to examine in the current study because it could help identify whether numerical skills are a deficit in individuals with DS, or whether the true deficit lies in the processing of symbolic numerical skills (i.e., Arabic numbers). If ANS is a relative strength in individuals with DS and the processing of symbolic numerical skills (i.e. identification of Arabic numbers) are found to be a weakness, then the current study would provide further support for the argument that individuals with DS have possible relative strengths in non-symbolic numerical skills, but challenges in symbolic numerical skills.

a. Early Development of Numerical Skills

Integrative theory of numerical development. Siegler and Lortie-Forgues (2014) proposed the integrative theory of numerical development. This theory presents the idea that the development of numerical abilities from infancy throughout adulthood is based on an increasing understanding of numerical magnitudes. It has been empirically supported by both causal and correlational studies that support the importance of understanding numerical magnitudes to developing numerical skills. For example, Libertus et al. (2011) found that preschoolers' performance on the dot task (which measures understanding of non-symbolic magnitude) predicted later math achievement. Also, Booth and Siegler (2006) found that accuracy with which a child can predict the placement of numbers on number lines predicted overall math achievement from kindergarten through middle school.

The integrative theory of numerical development divides numerical skills into four major groups, which emerge sequentially. The first is the representation of non-symbolic numbers. This is associated with the ANS, which is a non-symbolic magnitude representation system. A child demonstrates representation of non-symbolic numbers when they represent numerical quantities nonverbally without using number symbols (Siegler and Lortie-Forgues, 2014). The ANS is believed to be crucial to the development of all numerical skills and researchers have found that this basic numerical skill is predictive of math achievement in the future. For example, one study found evidence of an infant's recognition of differences in non-symbolic numerical magnitudes at 6 months of age to correlate with their math achievement at the age of 3 years old (Starr et al., 2013).

Whereas the first-emerging numerical skill of Siegler and Lortie-Forgues' (2014) theory is non-symbolic, the second and third numerical skills to emerge are symbolic; that is, they involve using number symbols to represent quantities. The second numerical skill is the ability to link non-symbolic and symbolic numerical representations. This is apparent when a child is able to connect a quantity of objects to the number correctly, such as if the child is asked to give someone 5 pieces of candy the child is able to associate the number 5 with the non-symbolic representation of the number (e.g., the candy representation of the number 5). Ultimately, the second numerical skill is the ability to master one's number sense. Studies have shown evidence of young children being slow to make the correct association of the number word (symbolic representation) to the quantity of objects representing that number (non-symbolic representation) (Le Corre et al., 2006). Another way to measure the transition between non-symbolic and symbolic numerical skills in the second numerical skill is to examine how well children can perform on a number line estimation task or symbolic magnitude comparison task. Children have begun to master this acquisition when they can accurately and consistently determine where Arabic numbers fall on a number line in comparison to other Arabic numbers, meaning they are able to differentiate which number is larger or smaller in comparison to other Arabic numbers. Studies have linked numerical line estimation skills and symbolic magnitude comparison skills to future math achievement scores (Geary et al., 2007).

The proposed study focuses on these first two acquisitions in individuals with DS. The third numerical skill is the ability expand their range of numbers, which is represented by a child's ability to count and apply the counting principles expanding their knowledge of symbolic skills. The fourth and final numerical skill to emerge is the cognitive ability to represent numbers other than whole numbers, e.g., fractions. The third and final acquisitions are beyond the scope of the current study, therefore they are not discussed at this time.

Non-Symbolic Numerical Skills. The ANS is a pre-verbal numerical system that guides the estimation of quantity, including judging the difference in quantity between two sets of items without using symbolic numerical skills. It is not a precise system; rather than using exact counting to differentiate the difference between two quantities, the ANS utilizes inexact representations of numbers (Gallistel & Gelman, 1992). The ANS is viewed as the non-symbolic representation of all numbers, which means that quantities are represented without any concepts of number symbols involved. The ANS is also assumed to overlap with estimation of non-numerical magnitudes.

A signature of the ANS is number acuity. Number acuity is the precision with which one can differentiate between two quantities and has been linked to mathematical achievement (Halberda et al., 2008). Quantities that are farther apart in numerical distance are easier to identify as different than quantities that are closer to one another in numerical distance (i.e., 2 vs. 10 compared to 2 vs. 3). This is also known as the distance effect. Individuals with greater number acuity are able to identify smaller differences in quantities than those with less numerical acuity. Further, larger numbers are more difficult than smaller numbers at the same numerical distance (i.e. 2 vs. 4 compared to 42 vs. 44) (Sella et al., 2013). In terms of number acuity, individuals with greater number acuity are able to identify larger numbers at the same numerical distance as smaller numbers than individuals with less number acuity.

Halberda and Feigenson (2008) used a cross-sectional design to assess the developmental trajectory of the ANS in TD individuals, ranging from 3 years old to adults. The study revealed that the ANS was already present in 3-year-olds. It also revealed that the ANS continues to develop throughout childhood and adolescence into adulthood because of individuals' abilities to notice smaller and smaller differences between two quantities, thereby resulting in greater number acuity skill (see also Piazza et al., 2010). In fact, evidence suggests that number acuity skill begins to increase very early in life. For example, 6-month-old infants are unable to discriminate between 8 and 12 items but can differentiate the two quantities of 8 and 16 (Carey & Xu, 2001), whereas 11-month-old infants are able to differentiate the quantities 4, 8, and 16 (Brannon, 2002).

<u>Symbolic numerical skills.</u> It is suggested that as ANS develops, symbolic representation of numbers (e.g., counting and learning the names of numbers and written numerals) slowly begins to sharpen, which leads to a shift from ANS to symbolic numerical skills, or non-verbal to verbal mathematics. Symbolic representation of numbers is apparent when a child learns to count and learns the names of numbers (see Le Corre et al., 2006). The distinction between non-symbolic and symbolic numerical skills is important in defining the role that the ANS plays in the development of numerical skills in children with DS and could possibly account for the differences that are observed in higher level numerical skills between individuals with DS and TD individuals (Porter, 2019). Porter (2019) provided empirical support for this important distinction in her review of the current literature on numerical skills in individuals with DS.

Counting is the foundation of symbolic numerical skills and over many years of research, five principles of counting have been identified (Gelman and Galistel, 1986). The first three principles of counting include: (1) stable-order principle, (2) one-to-one principle, and (3) cardinality principle. The first three principles of counting are believed to develop early in a child's development of numerical skills, while the other two principles ((4) abstraction and (5) order irrelevance) of counting are developed later in development as a child masters early numerical and language skills. Due to the current study's focus on early numerical, only the first three principles of counting are included here. The other two principles of counting are beyond the scope of the current study, and therefore they are not discussed at this time.

The stable-order principle states that numbers must be in a stable, repeatable order. This is the first principle to typically develop at a younger age when children are learning to count. Le Fevre et al. (2006) found evidence that kindergartners are able to master this principle. The stable order principle is believed to be followed by the one-to-one principle, which is apparent when children understand that each sequential number in order corresponds to one more object being counted. If, when counting objects, a child repeats a number, or skips a number, then they are still working to develop the first two principles of counting.

Next, the cardinality principle is apparent when children understand that the last number in a counting sequence represents the total number of objects counted (Butterworth, 2005). This principle corresponds with Siegler and Lortie and Forge's (2014) second numerical skill – linking symbolic and non-symbolic numerical representations because it allows one to be able to understand that the quantity represented by the total number of objects is represented by one symbolic number symbol. The cardinality principle is typically slow to develop, which can be seen in young children who can count from 1-10 but fail to give the researcher 5 pieces of candy when the researcher asks them to (Le Corre et al., 2006). It should be noted that mixed results of the exact age and order that these first three counting principles emerge has been seen across studies (Stock et al., 2009).

While the cardinality principle does correspond with Siegler and Lortie and Forge's (2014) second numerical skill, it is not the optimal measure because of its use of counting in its measurement. The optimal way to measure Siegler and Lortie and Forge's (2014) second numerical skill – linking symbolic and non-symbolic numerical representations is through the use of number line estimation, or another numerical task that measures the magnitude of numbers. A measure of magnitude in numerical skills, such as a number line estimation task, is the optimal measure because it allows one to measure an individual's understanding of the value that symbolic number words (i.e., Arabic number symbols) represent in relation to other Arabic numbers without the individual having to necessarily know how to say the number verbally or do any mechanical counting. This skill is believed to be predicted by the number system knowledge (LeFevre et al., 2013). Number line estimation (i.e., magnitude of numbers) is thought to predict one's ability to master the first three counting principles (Muldoon et al., 2013).

The current study uses a modified symbolic numerical task that measures the transition between non-symbolic and symbolic numerical skills using the same cognitive skills that are the measure of one's ability to master the magnitudes of numbers, such as is one aspect measured by numerical number line estimation and numerical magnitude comparison tasks. However, rather than using a number line estimation task, the current study uses the simple symbolic magnitude comparison task of Arabic numbers to determine whether participants are able to differentiate which Arabic number is larger in comparison to other Arabic numbers. This modified numerical magnitude task allows researchers to measure how well children understand the value of the symbolic number symbols (i.e., Arabic Numbers) in relation to other numbers without mechanical counting or verbally stating the symbolic number symbols (i.e., words for the Arabic numbers) in a design that is parallel to the dot task used to measure the ANS.

It is widely believed that counting skills rely on basic language abilities (Abdelhameed, 2007; King et al., 2017). This belief could be the reason numerical deficits in children with DS are seen because of the role that language and reading abilities play in the development of symbolic numerical skills. Further exploration into the development of numerical skills is needed to understand the differences between MA matched TD children and children with DS. The next section discusses what is known about numerical skills in children with DS with the hope of beginning to identify areas of numerical skills that may be of relative strength in individuals with DS compared to MA matched TD children.

b. Numerical Skills in Down Syndrome

Children with DS have been previously believed to have numerous deficits in numerical skills, including counting, basic arithmetic, and academic achievement in mathematics (Abdelahmeed, 2007; King et al., 2017; Brigstocke, Hulme, and Nye, 2008). However, when examining the empirical studies, it seems that children with DS may not have as profound deficits in numerical skills as previously believed. Understanding these numerical skills and whether they truly are a deficit or relative strength in children with DS is important to improving their independence and quality of life due to the major role numerical skills play in the development of adaptive skills, social skills, and other essential skills needed to function independently in everyday life (Schalock et al., 2007). These skills include cooking, counting change, reading a clock, as well as many other necessary skills needed in everyday life. Consistent with the TD literature, the study of the development of numerical skills in individuals with DS begins with examining the approximate number system (ANS).

Non-symbolic numerical skills in DS. Porter (2019) reviewed the current literature on numerical skills in children with DS, with a focus on the studies that examined the ANS. While the review suggested an optimistic view on children with DS' abilities to discriminate between quantities, it also brought attention to a few major methodological issues found within the current literature, including how children with DS are currently measured on numerical skills, such as the ANS, as well as inconsistency in ages of individuals with DS that have been tested in previous studies, and the lack of examining changes over time. For the purpose of the current study, four of the eight articles compared in the review are discussed in depth here. Only four of the eight studies are examined here because only four of the eight studies reviewed are relevant to the current study. The four studies not discussed here are beyond the scope of the current study, and therefore they are not discussed at this time.

Sella et al. (2013), Camos (2009), Abreu-Mendoza and Arias-Trejo (2015), and Belacchi et al. (2014) all examined the ANS in children with DS compared to TD children matched by MA. Belacchi et al. (2014) was the only study to find evidence of a deficit of the ANS in children with DS compared to TD children matched by MA, meaning that children with DS were worse at estimating numerosity compared to TD children matched by MA. Sella et al. (2013), Camos (2009), and Abreu-Mendoza and Arias-Trejo (2015) each found that children with DS were similar in their ability to discriminate between quantities compared with TD children matched by mental age (MA), which is consistent with the belief that the ANS is preserved in children with DS as a relative strength. For example, Abreu-Mendoza and Arias-Trejo (2015) used eye tracking as a nonverbal way of measuring whether individuals with DS could successfully discriminate between two quantities. They showed participants two sets of cartoon animals, side by side and asked, *Donde hay más? (Where are there more?)*. They found that, in general, participants looked longer at the side with the larger quantity, indicating quantity discrimination. Further, the looking time differential corresponded with ratio and TD age group as would be expected and was similar for DS and MA-matched groups. These results are consistent with those of Camos (2009) and Sella et al. (2013). Sella et al. (2013) found evidence of numerorsity being a relative strength in children with DS using the dots task.

Like Abreu-Mendoza, Arias-Trejo (2015), and Sella et al. (2013), Belacchi et al. (2014) also used a nonverbal method for measuring whether individuals with DS could discriminate between quantities. However, while children pointed to which of two side-by-side sets of dots had more, they were given 4 seconds to respond versus 2-2.5 seconds in other studies, such as Sella et al. (2013). This may have led the children to attempt to count the dots rather than using their judgment of which side had more dots, giving a disadvantage to participants with DS. Another difference that may have led to different results was that in each trial, participants compared arrays of varying numbers of dots to a standard array of 16 dots instead of using ratios of increasing difficulty. The comparison of varying arrays of dots to 16 did create ratios, but not consistently difficult or consecutively increasing ratios, which made differing ratios not an important element of the Belacchi et al. (2014) task. While all the studies do involve some form of ratios, the other studies used more consecutive and smaller ratios compared the ratios used in Belacchi et al. (2014). This is important because being able to identify how an individual increases in their skill and mastery of ratios as the ratios increase in complexity is how ANS can be measured overtime and in a quantifiable measurement. Belacchi et al. (2014) had a range of ratios that were mostly larger and more complex ratios compared to the other studies, which could be a reason why Belacchi et al. (2014) found children with DS to show deficits in the ANS while the other studies showed a more preserved ANS in children with DS compared to MA matched TD children.

On the other hand, Belacchi et al. (2014) had a larger sample size (N = 42) compared to the other three studies (N= 16; N = 12; N = 21), which means that it is possible Belacchi et al. (2014) was the only study to have enough power to detect a significant effect. Stella et al. (2013) had to exclude almost a third of their participants with DS because they were unable to complete the dots task, whereas Belacchi et al. (2014) and Abreu-Mendoza and Arias-Trejo (2015) were able to include all of their participants, and thus their results are based on the full range of ability in the sample. These are some of the possible reasons for varying results in the literature, but with so few studies and no direct replications yet there is not enough evidence to know with certainty whether children with DS have a preserved ANS or not. Most studies suggest that non-verbal numerical skills, such as numerosity (one of the numerical skills found within the ANS), , are a relative strength for individuals with DS, whereas verbal numerical skills, such as symbolic numerical symbols, are weaknesses in individuals with DS.,However, the results from Belachhi et al. (2014) demonstrate that the majority of the current literature's findings could be wrong.

c. Symbolic Numerical Skills in DS

Just like the literature on non-symbolic numerical skills in individuals with DS is divided on whether individuals with DS have a preserved ANS or not, the literature on symbolic numerical skills is also divided in suggesting that children with DS show deficits in their ability to connect the non-symbolic numerical skills and symbolic numerical skills. This is often measured using measures that examine one's mastery of numerical magnitude, such as the number line estimation task, in which individuals estimate the placement of an Arabic number on a number line. As mentioned already, the distinction between non-symbolic and symbolic numerical skills may play a crucial role in defining the role that the ANS plays in the development of numerical skills in children with DS, which could account for the differences in higher level numerical skills between individuals with DS and TD individuals. It is believed that children with DS learn and acquire the different principles of counting through repetition and mechanical teaching of these different principles, while TD children demonstrate a more implicit understanding of the counting principles (Gelman, 1982).

However, some studies have begun to suggest that children with DS may perform similarly to their MA-matched TD peers on certain counting principles, such as cardinality (Sella et al., 2013), one-to-one principle (Abreu-Mendoza & Arias-Trejo, 2017), and stable order Caycho et al. (1991). This suggests that children with DS may have a preserved understanding of at least a few of the basic principles of counting. Currently, three review papers have been published that focus at least in part on individuals with DS' ability to count and understanding of counting principles. Abdelahmeed (2007), King et al. (2017), and Brigstocke, Hulme, and Nye (2008) all reported at least some evidence that children with DS have deficits in counting skills compared to TD children but demonstrate at least some understanding of the first three counting principles (one-to-one, stable-order, and cardinality). However, all three reviews suggest that there are not enough studies to be able to draw accurate conclusions due to the various results and methodology used in the different studies. A further look into studies on numerical skills in individuals with DS may suggest that there may be fewer deficits in understanding of counting principles than previously believed.

Caycho et al. (1991) found evidence that children with DS are consistent with MA-matched TD children on all three counting principles. They used nine videos demonstrating three hand puppets counting five varying objects and had the children identify whether the puppet made an error or not while using the different counting principles. They found that children with DS were able to identify counting errors made by the puppets in the videos that violated the one-to-one principle, the stable-order principle, and the cardinality principle at about the same accuracy as the TD MA-matched children, meaning there were no statistical differences between children with DS and TD children matched by MA in their accuracy of identifying the various counting principle errors made by the puppets in the video. This suggests that children with DS have a relative strength in the first three counting principles. Similarly, Sella et al. (2013) found evidence that individuals with DS perform at their MA level on both cardinality and stable-order principles. They used a digits-to-dots task to measure cardinality, which involved having the participants determine whether an arrangement of dots correctly represented the target Arabic number presented. They used the counting subscale for Batteria Intelligenza Numerica (BIN) to measure the stable-order principle. The BIN counting subscale assesses a child's ability to recite a number sequence forward and backwards, as well as their understanding of the order of the Arabic numbers 1 through 5. Sella et al (2013) found that individuals with DS were not significantly different from MA-matched TD participants in their performance on the BIN counting subscale and the digits-to-dots task, suggesting that the stable-order and cardinality principles are preserved in individuals with DS on their MA ability.

Also, Abreu-Mendoza & Arias-Trejo (2017) found evidence of children with DS having a preserved one-to-one counting principle. However, instead of matching their TD and DS group by MA, like the previous studies, they matched TD and DS groups by their ability to count beyond three. After matching the groups by counting ability, they showed children videos consistent vs. inconsistent with the one-to-one counting principle and measured how long children looked at each video. They found that in both the TD and DS groups participants looked longer at the principle-consistent videos, which suggests that regardless of counting ability individuals with DS show some implicit understanding of the one-to-one counting principle.

These three studies suggest that individuals with DS may in fact not have serious deficits in understanding counting principles. However, Nye et al. (2001) found evidence that children with DS perform worse than MA-matched TD peers on both the stable-order and cardinality counting principles. They asked children to help puppets count varying objects, recording the highest number sequence the children could recite to measure the stable-order principle, and then they used a give x task, which involved asking the children to count x number of objects in a set into a basket, to measure cardinality. They found that children with DS recited shorter number sequences than MA-matched TD participants and correctly counted smaller x sets than MA-matched TD participants, suggesting a deficit in both the stable-order and cardinality principles. However, they also found that children with DS were just as likely as the TD children to use counting in the give x task, which suggests that, despite their deficits in their mastery of the cardinality principle, children with DS show an implicit understanding of the cardinality principle. The results of Nye et al. (2001) suggest that the review papers may be right in that children with DS may show deficits in counting even if they have a basic understanding of the stable-order, one-to-one, and cardinality principles.

However, as mentioned in the three review papers, it is important to consider the measures used within the studies. No one study has used the exact same methods or measures and the three studies (Caycho et al., 1991; Sella et al., 2013; Abreu-Mendoza & Arias-Trejo, 2017) that suggested a preservation of counting skills in individuals with DS all employed non-verbal counting tasks, whereas Nye et al. (2001) employed verbal counting tasks. This suggests that verbal ability may be the reason for deficits identified in individuals with DS and measures that employ verbal methods of measuring numerical skills may not be as accurate as non-verbal measures of numerical skills in individuals with DS. This idea is suggested in all three reviews (Abdelhameed, 2007; King et al., 2017; Brigstocke et al., 2008). Clarifying how individuals with DS develop the first three counting principles could provide valuable insight into further understanding various reasons for deficits in numerical skills seen in individuals with DS.

As well as understanding how individuals with DS develop the counting principles, it is important to examine how individuals with DS develop the connection between the symbolic and non-symbolic numerical skills without including mechanical counting in the measure. This is examined by looking at individuals with DS performance on symbolic magnitude comparison tasks, such as numerical line estimation tasks. Simms et al. (2020) used a numerical line estimation task to examine the difference between individuals with DS across a wide age range (8.06 - 49.17 years) and MA-matched TD children (4.5 - 10.2 years). The numerical line estimation task involved the researcher asking the individuals if one end is 0 and one end is either 10 or 100, depending on whether they were in the 0-10 task or the 0-100 task that were completed by all participants, then where would x fall and having the individuals point to where they would place the number x on the number line. They found that there were no significant differences in performance in the number line estimation task between DS individuals and the MA-matched TD children, which suggests that individuals with DS may possess the ability to connect the symbolic and non-symbolic numerical skills. This idea is consistent with individuals with DS having at least a basic implicit understanding of counting principles because to understand counting principles one must link symbolic and non-symbolic numerical skills together.

With few studies examining the ANS, counting principles and the link between non-symbolic and symbolic numerical skills in children with DS, it is difficult to know whether children with DS have some relative strengths or deficits in the ANS, the stable-order principle, one-to-one principle, cardinality principle, or symbolic magnitude comparison tasks. It is known that both TD children and children with DS are born with a predisposition to learn the ANS and the ANS is the foundation for more advanced numerical skills. Whether children with DS are consistent with MA matched TD children in the ANS, suggesting the ANS as a relative strength in children with DS, remains an unanswered question. It is also known that both TD children and children with DS need to have mastered the ability to mechanically count before they can master the conceptual understanding of the various counting principles (Porter, 1998; Porter, 1999). The question remains as to whether children with DS master the mechanical ability to count consistent with how MA matched TD children master the ability to mechanically count or not. Lastly, it is known that the linking of non-symbolic numerical skills to symbolic numerical skills predicts one's ability to master the counting principles in both TD children and children with DS. Whether or not the transition of linking non-symbolic numerical skills (ANS) to symbolic numerical skills (i.e., Arabic numbers) is a relative strength in children with DS or not is still unknown. If the transition of the linking between non-symbolic numerical skills and symbolic numerical skills is a deficit in children with DS then the second acquisition of numerical skills may be where children with DS begin to fall behind MA matched TD children in their development of numerical skills.

Determining where children with DS have relative strengths in numerical skills and where deficits in numerical skills begin to appear is important to understanding the possible reasons for the deficits in numerical skills in individuals with DS. Are these deficits due to language and memory deficits, or other factors, such as the way the counting principles and numerical skills are taught in schools? The belief that children with DS are consistent with MA matched TD children on the ANS, first three counting principles, such as the cardinality principle (Sella et al., 2013) and the number line estimation task (Simms et al., 2020) suggests that the language skills required to say the number words and the memory skills required to know that each number word corresponds to each appropriate quantity of objects may be a likely source of children with DS's deficits in numerical skills. The first step to uncovering the reason behind children with DS's deficits in numerical skills is to examine the first two acquisitions of numerical skills and determine whether they are relative strengths for individuals with DS or deficits. This is the aim of the current study.

d. The Current Study

One of the main difficulties in interpreting the results of symbolic and non-symbolic numerical skills is the range of tasks used to measure each. Previous studies used widely different measures for the ANS and the symbolic numerical skills. The current study aimed to help address this issue by using measures of ANS and symbolic numerical skills that are similar in design, but still accurately measure the first two acquisitions of numerical skills. Using similar designs should allow for the link between non-symbolic and symbolic numerical skills to be examined in a more straightforward manner. These similar designs should provide the individuals with DS a measure of both non-symbolic and symbolic numerical skills that is matched for their skill set and consistent with the cognitive processes measured in the first two acquisitions of numerical skills. This allows researchers to begin to possibly identify specific challenges and strengths that individuals with DS may have, such as the ANS and a modified symbolic magnitude comparison task. *Regarding non-symbolic numerical skills, it was hypothesized that individuals with DS will perform at a similar level on a non-symbolic numerical task when compared to TD participants matched by MA. Regarding symbolic numerical skills, it was hypothesized that individuals with DS will perform below their MA-matched TD peers on a similar symbolic numerical task.*

Another difficulty in interpreting the results of the symbolic and non-symbolic numerical skills is that the DS group is matched with the TD group based on mean MA. This ignores the possibility that group performance may compare differently at various levels of MA. For example, it is possible that at a low MA (e.g., 3 years), groups are similar on numerical skills, but as MA increases, the groups diverge. This may happen if development of numerical skills is slower than overall development in children with DS. Thus, the current study examined two sets of regression analyses. The first set of regression analyses examined non-symbolic numerical skills performance across MA separately for individuals with DS and MA-matched TD children, while the second set of regression analyses examined the transition from non-symbolic to symbolic numerical skills, using a modified symbolic magnitude comparison task, across MA separately for individuals with DS and MA-matched TD children. *Regarding non-symbolic numerical skills, it was hypothesized that the slopes for non-symbolic numerical skills will be similar across groups. Regarding symbolic numerical skills, it was hypothesized that the slope for symbolic skills will be steeper for TD participants than the slope for participants with DS.*

2. METHODS

a. Participants.

Thirty-one Children with DS between the ages of 6 and 15 years old were recruited from a range of states in the U.S. via the University of Alabama Intellectual Disabilities Participant Registry, and word of mouth (M_{age} = 10.94, SD_{age} = 2.42; 58.1% female, 49.9% male; 80.6% White, 9.7% African American, 9.7% Asian).

Forty TD children between the ages of 4 and 6 years old were recruited from a range of states in the U.S. via Safe Haven Church, word of mouth and social media platforms (M_{age} = 5.38, SD_{age} = 0.82; 47.5% female, 52.5% male; 78.4% White, 2.7% African American, 10.8% Asian, 8.1% Multiple ethnicities).

Inclusion in the study for both TD and DS groups required that participants had (1) knowledge of Arabic numbers, (2) used English as their primary language, and (3) had a parent/guardian that was able to complete the background questionnaire. These enrollment criteria were checked by the researcher by asking parents/guardians during the recruiting process. If a parent/guardian answered “no” to their child being able to meet any of the inclusion criteria, then the parent was kindly informed that their child was not a good fit for the current study.

For both groups, participants were excluded for one

of three reasons: (1) failure to complete the entirety of either or both of the numerical tasks, (2) not being attentive on one or more of the numerical tasks, which was measured using the task that Hessl et al.(2016) used to verify that the tasks he included in the NIH Toolbox were valid, and (3) fails to correctly identify more than 5 numbers in the Numerical Knowledge Check. The exclusion of participants that scored 5 or less on the Numerical Knowledge Check was because participants that were unable to identify at least 6 out of 35 numbers on the Numerical Knowledge Check did not have enough knowledge of their Arabic numbers to obtain a valid measure of the Symbolic Numerical Skills Task. A total of 6 participants were excluded from all analyses. 1 participant with DS was excluded from all three analyses due to failure to complete both numerical tasks. 2 participants with DS and 1 TD participant were excluded from all three analyses due to having scored 5 or less on the Numerical Knowledge Check. Lastly, 2 TD participants were excluded from all three analyses due to being marked inattentive on the Symbolic Numerical Skills Task.

Participants were compensated for participation in the study with a sticker that was mailed to their home address after they had completed their final testing session.

b. Measures.

Background Questionnaire. The purpose of this questionnaire was to collect background information on the participants that may provide helpful insight into differences between numerical skills. The questionnaire was completed by the parent, or guardian, via a Qualtrics Survey that was designed for the current study. The questionnaire included demographic information, such as participant age, race, and family income, as well as some other key variables related to the development of numerical skills, such as grade, type of school, type of math education (whether the participant is in the classroom for math, or in a special class), type of classroom environment, at home numerical practice, etc. The questionnaires were coded by the participant ID and emailed to the parents/guardians via an anonymous link to the Qualtrics survey. Most parents/guardians were able to complete the questionnaire in about 15 minutes prior to the start of the second testing session.

Peabody Picture Vocabulary Test- Fifth Edition (PPVT-5; Dunn, 2019). The PPVT-5 is a standardized nonverbal test of receptive vocabulary that requires participants to look at 4 pictures on each page and point to the picture that corresponds with the word spoken by the experimenter. It can be administered to individuals that are 2.5 years old and up. The test covers 20 content categories and includes knowledge of various nouns, verbs, and adjectives. The PPVT-5 was selected as a measure of MA for the current study because of its use of verbal skills and because of its excellent overall reliability of .97 (Dunn, 2019). Furthermore, this test was selected for its usefulness in measuring nonverbal receptive vocabulary in children with DS and young children because of its low floor, colorful pictures, and nonverbal response requirements. Also, it provides a Growth Value Score (GSV), so it is ideal for the current study. This test was chosen as the measure of MA, over other similar cognitive ability tests, because of the verbal component and the GSV provided.

PPVT-5 was modified to administer via video conferencing service over Zoom. To accomplish this, a colored star was placed under every picture on each page with each color corresponding to the same number on each page (1 = Blue, 2 = Yellow, 3 = Red, & 4 = Green). The child was asked to point and place their finger on the picture that best matched the word for their answer. Before the child could remove their finger from the picture, either the child or their guardian verbally told the researcher the color that was directly below the picture.

Numerical Knowledge Task. To determine whether the participants know the numbers 1 to 35, the researcher presented PowerPoint slides with each slide having one number between 1 to 35 on them and asked the participant to tell them aloud what they thought each number was.

The numbers were randomized using an online random number generator. The purpose of showing the numbers in a random order was to control for counting skills. Each participant saw the numbers in the same random order and completed the Numerical Knowledge Task prior to completing the Symbolic Numerical Task. The number of numbers the participant correctly identified was recorded. Participants that correctly identified 6 or more numbers were included in the analyses. 6 or more correct was chosen as the cut-off for the current study because participants that were able to identify at least 6 of the 35 numbers seemed to have enough knowledge of Arabic numbers to complete the Symbolic Numerical Skills Task with a valid score. Only 3 out of 71 participants (1 DS and 2 TD) failed to meet the criteria of 6 or more correct answers on the Numerical Knowledge Task. The possible range of scores for the Numerical Knowledge Task was 0 to 35.

<u>ANS Acuity Task.</u> To measure children's non-symbolic numerical skills, the researcher administered a non-symbolic number comparison task modified from ANS acuity tasks used in the preschool litertaure (Halberda et al., 2008; Libertus et al., 2011; Mazzocco et al., 2011). In this task participants were presented with side-by-side arrays of blue and yellow dots on a computer screen. Prior to the beginning of each trial, participants were first presented with an attention screen that asked the participants to look directly at Mickey Mouse in the center of the screen. Following the attention screen, each trial had arrays of blue and yellow dots appear for 2000ms followed by a screen with a blue and a yellow star. The blue dots and blue star were always on the left side of the screen and the yellow dots and yellow star were always on the right side of the screen. The dots ranged in size and quantity for each trial to help control for the possibility of size and area affecting the results. Participants had to indicate whether Yellow or Blue had more dots on their side. To answer, they were asked to point to the corresponding-

colored star and verbally report whether they were pointing to the blue or yellow star. The researcher pressed a “Y” key for Yellow or “B” key for Blue to indicate which array they had selected for their answer. If participants were nonverbal, or soft-spoken, then the parent/guardian answered the color that the participant had selected. The dots appeared on the screen for 2000ms to prevent the participant from being able to count the items. Each trial was initiated by the researcher once they felt the participant was paying attention to the attention screen and ready to begin the trial. Blue and yellow dots always appeared on the same side followed by the corresponding-colored stars. (See Appendix A for example.)

Each participant completed a total of 54 trials. There were six practice trials to familiarize the participant with the game. Following the practice trials, the participants completed 48 test trials. Test trials were randomly drawn by the computer program, SuperLab, from one of four numerical ratio bins: 1:2, 2:3, 3:4, and 4:5. The number of dots in each trial varied, such that 4 dots versus 8 dots went into the 1:2 ratio bin. For half of the trials Blue had more dots and for the other half of the trials Yellow had more dots. The average size of the dots was equal on half of the trials and the cumulative surface area of the dots were equal across both arrays for the other half of the trials. Answers were recorded for each array in the computer. An overall number of correct responses was computed, as well as individual totals for each ratio category was collected to help determine mastery of the individual ratios. The overall number of correct responses was used as the overall ANS score for the data analyses. The possible range of scores for the ANS Number Acuity Task was 0 to 48.

<u>Symbolic Numerical Task.</u> To measure the symbolic numerical ability of the participants, researchers used a modified computerized symbolic numerical magnitude comparison task like the one used by Price and Wilkey (2017). The task was adapted down to the skill-level of the

current participants. In this task, participants were presented with two side-by-side numbers (1 Blue number on the left and 1 Yellow number on the right) on a computer screen. Prior to the beginning of each trial, participants were first presented with an attention screen that asked the participants to look directly at Mickey Mouse in the center of the screen. Following the attention screen, each trial had a blue number and yellow number appear for 2000ms followed by a screen with a blue and a yellow star. The blue numbers and blue star were always on the left side of the screen and the yellow numbers and yellow star were always on the right side of the screen. The numbers were the same size and same area for each trial to help control for the possibility of size and area affecting the results. Participants had to indicate whether the yellow or blue star had the larger number on its side. To answer, participants pointed to the corresponding-colored star and verbally reported whether they were pointing to the blue or yellow star. The researcher pressed a "Y" key for Yellow or "B" key for Blue to indicate which number the participant had selected for their answer to that trial. If participants were nonverbal, or soft-spoken, then the parent/guardian answered the color that the participant had selected. The numbers appeared on the screen for 2000ms to keep the task parallel with the ANS acuity task. Each trial was initiated by the researcher once they felt the participant was paying attention and ready to begin the trial. Blue and yellow numbers always appeared on the same side followed by the corresponding-colored stars, such that blue numbers and blue star were always on the left and yellow numbers and yellow star were always on the right. (See Appendix B for example.)

Parallel to the ANS Acuity Task, each participant completed a total of 54 trials. There were six practice trials to familiarize the participant with the game. Following the practice trials, the participants completed 48 test trials. Test trials were randomly drawn by the computer program, SuperLab, from one of four numerical ratio bins: 1:2, 2:3, 3:4, and 4:5. The number pairs in each trial varied, such that 4 versus 8 went into the 1:2 ratio bin. The number pairs in the Symbolic Numerical Skills Task were the same exact pairs as the number of dots in each pair of dot arrays in the ANS Acuity Task to make sure the two numerical tasks were parallel in design. For half of the trials Blue had the larger number and for the other half of the trials Yellow had the larger number. The size of the numbers was equal on all.Answers were recorded for each number pair in the computer. An overall number of correct responses was computed, as well as individual totals for each ratio category was collected to help determine mastery of the individual ratios. The overall number of correct responses was used in data analysis, similar to the ANS Acuity Task. The possible range of scores for the Symbolic Numerical Task was 0 to 48.

Woodcock Reading Mastery Test- Third Edition (WRMT-III, Woodcock, 2011). The WRMT-III is a comprehensive measure of reading skills for ages 4.5 to 75+ years old and includes various subtests. The current study used the Letter Identification and Word Identification subtests to measure reading skills. These two reading skills measures were added into the study to examine the possible relationship between reading and numerical skills. Both subtests were presented on an easel where the participants were asked to identify the letter (letter identification subtest) or the word (word identification subtest) that were presented on each page of the easel. For Word Identification subtest, the split-half reliability is .85 - .98 across all ages. The total number of correctly identified letters was used as the score for the Letter Identification Subtest and scores were able to range from 0 to 17. The total number of correctly identified words was used as the score for the Word Identification Subtest and scores were able to range from 0 to 35.

Validity Tracker. The validity tracker was a checklist that was modified based off a validity tracking tool used by Hessl et al. (2016). The validity tracker was a checklist with 6 reasons that a task may be invalid. This allowed the researcher to record a judgment of how valid the measure of a participant's score was for each task based on the quality of the child's attention during the task. The validity checklist included six different reasons that a measure could be invalid. The six reasons for an invalid measure were: (1) needed excessive prompting, (2) refused to be part of all of testing, (3) invalid pattern response, (4) technical difficulties, (5) participant ill/emergency, and (6) other. If other was selected for a task, then further explanation why they were marking the task as invalid was provided. If the participant was attentive during the task, then the researcher marked the measure as valid. This especially was important due to this being one of the first studies to use remote testing over Zoom completed with special populations. (See Appendix C for example.)

c. Procedures.

The current study was conducted online due the COVID-19 Pandemic, so all of the procedures were designed with that in mind.

Prior to inviting the participant to complete the study, the researcher checked with the parent/guardian for inclusion criteria. For those who were included in the study, the researcher had the parent/guardian complete the informed consent form and were asked to schedule two Zoom Testing Sessions for their child. Once both testing sessions were scheduled, the parent/guardian received an email with the participant ID, two separate Zoom links so each participant and each session had a unique link, and an optional instructional video that introduced the parents to the study and what to expect with Zoom and tasks during the duration of the study. Most of the parents/guardians completed the background questionnaire prior to the final testing session, but some parent/guardians completed it after the final session. The researcher followed up the day of each testing session a few hours before a child was scheduled to answer any questions the parent/guardian might have had about how the study would work.

When the time scheduled for a testing session came around, the researcher logged into Zoom and waited for the participant to join the waiting room. Once in the waiting room, the researcher admitted the participant to the session and greeted both the participant and the parent/guardian. Each testing session began with the researcher introducing themselves and the purpose of the study, as well as the task(s) that were to be completed in that particular testing session and obtain verbal assent from the participant. If the participant said no to wanting to participate in the study, then the researcher ended the session regardless of whether the parent/guardian had given consent. The researcher explained that the parent/guardian was needed next to their child to help operate Zoom, tell the researcher the answer their child pointed to or said in a not clear manner for the researcher to make sure they got accurate answers recorded for each participant for each task, and help the researcher keep their child on task, but reminded the parent/guardian that they could not help their child by repeating items or trying to give hints or explain tasks differently nor could they let their child know whether they were getting any questions correct or incorrect. If there were any particular settings that were needed for a specific task that session, then the researcher walked the parent/guardian through how to make sure their settings on Zoom were correct for each task.

After gaining verbal assent from the participant, the researcher had the participant complete the PPVT-5 in the first testing session. This was completed by showing the pages over Zoom and the participant pointed to the picture and verbally replied with the color of the star underneath each picture. If participants were nonverbal or shy, then the parent/guardian verbally replied with what color matched the picture the participant had pointed to. Participants were able to complete the first testing session within 30 to 60 minutes. The researcher marked whether the PPVT-5 testing was valid using the attention measure described in the measures section.

In the second testing session, the researcher began the same way as they did the first one, but instead of introducing themselves they spent a few minutes talking with the child to get them more comfortable interacting with the researcher. Following the small talk, the researcher explained Zoom settings and the remaining tasks that the child would be completing during the second testing session. Half of the participants began their second testing session with the Numerical Knowledge Task and half of the participants began their second testing session with the ANS number acuity task to use counterbalancing to avoid possible order effects. Odd number participants in both TD and DS groups completed the remaining tasks in the following order: (1) ANS, (2) Numerical Knowledge Task, (3) Symbolic Numerical Task, (4) Letter Identification Task, and (5) Word Identification Task. Even number participants in both TD and DS groups completed the remaining tasks in the following order: (1) Numerical Knowledge Task, (2) Symbolic Numerical Task, (3) ANS, (4) Letter Identification Task, and (5) Word Identification Task.

At the start of each numerical computer task, the researcher explained the task to the participant and had them complete all 54 trials, beginning with the 6 practice trials followed by 48 test trials. The researcher marked whether the task was for valid immediately after each computer task using the attention measure described in the measures section.

Once participants had completed all 54 trials of their first numerical computer task, the researcher made sure the participant was ready to move onto the next task. If the researcher felt that the participant needed a break, then they suggested one before continuing with the remaining tasks. If the participant was no longer wanting to continue with the remaining tasks for the second session, then the researcher scheduled a third testing session to complete the missing computer numerical task and WRMT-III subtests, as well as numerical knowledge check for participants who completed the ANS number acuity task in the second testing session. If a third testing session occurred it was run just like the second testing session had been, except it only included the remaining incomplete tasks. Third testing sessions were only scheduled for participants who still had a numerical computer task left to complete. If the participant refused to do the letter and word identification tasks, then the second testing session ended, and the scores were marked as missing data for those tasks.

Whether in the same testing session, which was the case for majority of the participants, or whether in a third testing session, the participant completed the remaining numerical computer task. If it was the symbolic numerical task, then the numerical knowledge check was completed prior to the computer numerical task. Using the attention measure, the researcher marked whether the task was deemed valid or not for that participant.

Following the completion of their final numerical computer task, the researcher checked in on the participant to see whether they may need a break or not. The breaks in the second testing session only happened following each numerical task. Most participants chose to continue straight onto the WRMT-III subtests without a break. However, there was a small number of participants that refused to complete the WRMT-III subtests and ended their testing sessions after their final numerical computer task.

The WRMT-III subtests began with Letter Identification, where the researcher asked the child what letter(s) they saw on each page of the WRMT-III easel. Every participant that completed this task was able to complete the entirety of the letter identification subtest and score a perfect or nearly perfect score, which meant the Letter Identification Subtest had a ceiling effect that made the subtest invalid.

The last WRMT-III subtest was completed immediately following the Letter Identification subtest. The subtest was the Word Identification subtest, where the researcher asked the child what word(s) they saw on each page of the WRMT-III easel. About half of the participants refused to complete the task or were unable to meet the basal rule of 4 nonconsecutive correct words, which meant the Word Identification Subtest had a floor effect that made the subtest invalid.

Once the participant had completed all their tasks, the researcher thanked them for their help and told them to be on the lookout for a surprise in the mail. The researcher asked the parent/guardian to please text or email them their address so the participant could receive their compensation of a "Build Your Own Animal Face" Sticker sheet with a personal handwritten thank you note from the researcher in the mail. If the parent/guardian had not completed the background questionnaire yet, then the researcher reminded them to please complete and resent the link to background questionnaire with participant's ID and told the parent/guardian to text, call, or email them if they had any questions while completing it. The researcher then ended the final testing session.

3. RESULTS

All data analyses were carried out using SPSS statistical software. First, descriptives statistics, including mean, standard deviation, and range were calculated for all of the major variables for both TD and DS Groups (see Table 1 below).

a. Letter & Word Identification

To begin to explore the relationship between reading skills and numerical skills, two subtests from the Woodcock Reading Mastery Test were included in the study. The two subtests included were the Letter Identification Subtest and the Word Identification Subtest. Neither of these subtests were able to be used in any analyses due to the Letter Identification Subtest having a ceiling effect, meaning that majority of participants (75%) that completed the task scored at least 16 out of 17, with most participants having a perfect score of 17 out of 17 (57.7%), and the Word Identification Subtest having a floor effect, meaning too many participants were unable to meet even the basal rule, which made the subtest an invalid measure for this study. 46% of all participants from both groups that completed the Word Identification Subtest failed to meet the basal rule of 4 nonconsecutive correct words. Both subtests had a lot of missing or incomplete data as well, which also made them invalid. The Letter Identification Subtest had 19 participants with missing or incomplete data and the Word Identification Subtest had 21 participants with missing or incomplete data, which is greater than 25% of all participants excluded from both subtests. Means and standard deviations are included in descriptive tables below (Table 1), but these two subtests were not included in any analyses due to being invalid subtests.

Table 1.

Means, Standard Deviations (SD), and Ranges Main Variables by Participant Type

	DS *(N = 25)*			TD (*N = 24)*		
	Mean	SD	N	Mean	SD	N
Age	133.67	28.83	24	60.45	8.89	22
	Range = 83-186			*Range = 48-77*		
PPVT-5 GSV	473.28	7.79	25	474.75	5.83	24
	Range = 461- 496			*Range = 460-482*		
ANS	30.64	4.54	25	34.17	3.57	24
	Range = 22-39			*Range = 27-42*		
Symbolic	31.48	4.76	25	31.38	7.04	24
	Range = 25-44			*Range* = 21-45		
Numerical	26.60	8.75	25	20.29	11.39	24
Knowledge	*Range = 7-35*			*Range = 7-35*		
Letter ID	15.81	2.32	16	14.94	2.90	18
	Range = 10-17			*Range = 9-17*		
Word ID	16.88	12.35	17	3.88	6.32	16
	Range = 0-36			*Range = 0-23*		

Note. PPVT-5 GSV- Peabody Picture Vocabulary Test (5th Edition) Growth Score Value. Age- Chronological age in months. ANS- Overall total number correct on ANS Number Acuity Task. Symbolic- Overall total number correct on Symbolic Numerical Task. Numerical Knowledge- Total of correctly identified numbers from the Numerical Knowledge Check. Letter ID- Raw score for WRMT-III Letter Identification Subtest. Word ID- Raw score for WRMT-III Word Identification Subtest. Different sample sizes are due to missing data.

b. Group Differences on Numerical Tasks.

One of the main difficulties in interpreting the results of symbolic and non-symbolic numerical skills is the range of tasks used to measure each. Using parallel designs allowed for the link between non-symbolic and symbolic numerical skills to be examined in a more straightforward manner. These parallel designs provided measures of both non-symbolic and symbolic numerical skills that were matched for their skill set and consistent with the cognitive processes measured in the first two acquisitions of numerical skills. This allowed researchers to begin to possibly identify specific deficits and strengths that individuals with DS may have, such as the ANS and a modified symbolic magnitude comparison task. Regarding non-symbolic numerical skills, it was hypothesized that individuals with DS will perform at their developmental level on a non-symbolic numerical task. Regarding symbolic numerical skills, it was hypothesized that individuals with DS will perform below their developmental level on a parallel symbolic numerical task.

<u>Preliminary Analyses.</u> To check for normality, histograms were run, and no violations of normality were found. As stated above in the participants section, participants from both groups with invalid or incomplete scores on either ANS or Symbolic tasks were excluded from the 2x2 ANOVA and participants with a numerical knowledge score of 5 or less were excluded from all analyses. One participant with DS was excluded from all analyses due to an invalid measure of ANS and an incomplete measure of Symbolic Numerical Skills. Two participants with DS and one TD participant were excluded from all analyses due to having obtained a numerical knowledge score of 5 or less. Two additional TD participants were excluded from all analyses due to invalid measure of Symbolic Numerical Skills.

An independent samples t-test was run to check for similarity between groups on PPVT-5 GSV Scores, the matching measure. The initial t-test revealed that there were significant differences between the TD group (*M* = 478.43, *SD* = 8.006) and the DS group (*M* = 471.68, *SD* = 9.239) on PPVT-5 GSV Scores, $t(69) = 3.293$, $p = .002$. To be able to run the 2x2 ANOVA both groups needed to be equal on PPVT-5 GSV scores to allow for a valid comparison of group differences between the two groups on the numerical tasks. To address the issue of unequal PPVT-5 GSV Scores between the 2 groups, TD participants with a PPVT-5 GSV Score greater than or equal to 483 and DS participants with a PPVT-5 GSV Score less than 460, as well as the participants described above, were eliminated from the analysis for the 2x2 ANOVA. Eliminating participants helped create groups that were equal on PPVT-5 GSV for the 2x2 ANOVA, which led to 25 DS participants (*M* = 473.28, *SD* = 7.792) and 24 TD participants (*M* = 474.75, *SD* = 5.825) included in the 2x2 ANOVA, $t(47) = .746$, $p = .460$.

Main Analyses. To compare performance of participants with DS and TD participants matched by MA on the ANS and Symbolic Numerical Skills Tasks, a 2 (Group: TD, DS) x 2 (Task: ANS, Symbolic Numerical Skills) repeated measures analysis of variance (ANOVA) using PPVT-5 GSV Scores was conducted. There were no significant main effects for Task, $F(1, 47) = .793$, $p = .378$, or Group, $F(1, 47) = 2.601$, $p = .113$. While the interaction looks to be trending towards significant, there was no significant interaction between Task and Group, $F(1, 47) = 3.580$, $p = .065$.

This analysis revealed that there were no significant differences between the DS and TD groups for both ANS and Symbolic Numerical Skills, meaning that both groups performed at similar levels for both numerical tasks (non-verbal and verbal). However, this analysis only examined the mean differences and did not examine whether there were significant differences in growth in either numerical skill over MA across the two-groups. This ignores the possibility that group performance may compare differently at various levels of MA.

c. Regression Analyses

Thus, the current study examined two regression analyses. The first set of regression analyses examined non-symbolic numerical skills performance across MA separately for individuals with DS and MA-matched TD children, while the second set of regression analyses examined the transition from non-symbolic to symbolic numerical skills, using a modified symbolic magnitude comparison task, across MA separately for individuals with DS and MA-matched TD children. Regarding non-symbolic numerical skills, it was hypothesized that regression analyses for non-symbolic skills will have similar slopes across groups. Regarding symbolic numerical skills, it was hypothesized that the regression analyses for symbolic skills will have a steeper slope across PPVT-5 GSV scores for TD participants than for participants with DS.

Preliminary Analyses. Two separate regression analyses, one for TD participants and one for participants with DS, were conducted using the guidelines set forth by Thomas et al. (2009). We tested for differences at onset for overall ANS scores and overall Symbolic Numerical Skills scores over MA (PPVT-5 growth score values (GSV). Growth score values were chosen instead of age equivalence scores from the PPVT-5 due to being optimal for regression analyses. Onset was set to the lowest PPVT-5 growth score measured across participants, excluding the participants that were excluded from the analysis, (PPVT-5 GSV = 460) to allow for an easier comparison of the slopes between the two groups.

To determine whether any points were exerting undue influence on the regression analyses, Cook's D values were generated separately for each numerical task. In no case was

Cook's D above 1.00, so no points were removed from the analyses. Using scatterplots and visual inspection, no clear nonlinear trends were observed.

Using the guidelines set forth by Thomas et al. (2009), an adapted form of analysis of covariance (ANCOVA) in SPSS's General Linear Model was used to compare the regression slopes. The first set of regression analyses examined was ANS across MA and the second set of regression analyses examined was Symbolic Numerical Skills across MA, each comparing groups with DS vs TD. Unlike a typical ANCOVA, the covariate was not assumed to vary evenly across all levels of the dependent variable, which is typically assumed in an ANCOVA. In each of the individual regression analyses, the covariate was GSV PPVT-5 with the Group (TD, DS) as the independent variable and each individual numerical task (either ANS or Symbolic Numerical Skills) as the dependent variable. For each of the numerical tasks, the score used in analyses was the total number of answers answered correctly. Group differences between children with DS and MA-matched TD children for the two numerical tasks across PPVT-5 GSV were examined by looking at its intercept, which represents the group main effects, and slope, which represents the group x PPVT-5 GSV interaction. A significant main effect of groups means there is a difference between the two groups at the point of onset. A significant interaction between groups and PPVT-5 GSV means that a difference between the two groups in the score on the numerical task across PPVT-5 GSV. This process was used for each regression analysis below.

<u>ANS Regression Analyses</u>**.** See Figure 1 for a graphical representation of the regression analyses for ANS across MA, which is represented by PPVT-5 GSV scores. Results showed no statistical difference between the two groups in overall ANS scores at onset, $F(1, 45) = .300$, $p = .586$, $\eta^2 = .007$, which means that at onset TD participants and participants with DS were

performing at a similar level. PPVT-5 GSV scores were a strong predictor of overall ANS scores across both groups, $F(1, 45) = 22.193$, $p < .001$, $\eta^2 = .330$. However, results showed no statistical difference between the groups in slope of ANS scores across PPVT-5 GSV, as the interaction was not significant, $F(1, 45) = 0.643$, $p = .427$, $\eta^2 = .014$, which means that the DS and MA-matched TD groups did not differ in ANS task performance across the range of PPVT-5 GSV. Overall, the results of the regression analyses suggests that individuals with DS are neither delayed nor behind their developmental level for ANS numerical, which provides support for both hypotheses in terms of non-symbolic numerical skills.

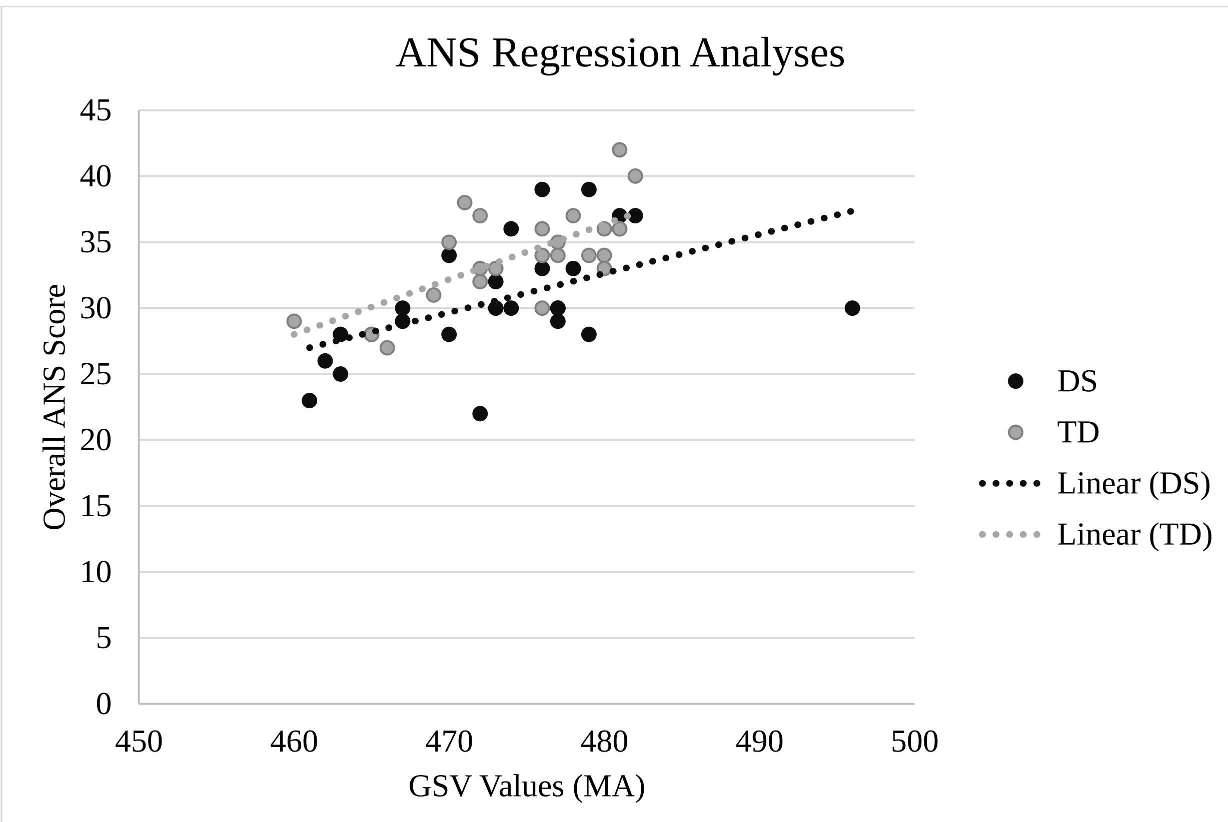

Figure 1. Overall ANS Scores over PPVT-5 GSV Scores

<u>Symbolic Numerical Skills Regression Analysis.</u> See Figure 2 for a graphical representation of the regression analyses for overall Symbolic Numerical Scores across MA, which is represented by PPVT-5 GSV scores. Results showed no statistical difference between

the two groups in overall Symbolic Numerical scores at onset, $F(1, 45) = 2.556$, $p = .117$, $\eta^2 = .054$, which means that at onset both TD participants and participants with DS were performing at a similar level. PPVT-5 GSV scores were not a significant predictor of overall Symbolic Numerical scores across both groups, $F(1, 45) = 3.376$, $p = .073$, $\eta^2 = .070$. Furthermore, results showed no statistical difference between the groups in slope of ANS scores across PPVT-5 GSV, as the interaction was not significant, $F(1, 45) = 3.189$, $p = .081$, $\eta^2 = .066$. This means that the DS and MA-matched TD groups did not differ in Symbolic numerical skills performance across the range of PPVT-5 GSV. Overall, the results of the regression analyses suggest that individuals with DS are neither delayed nor behind their TD peers matched by PPVT-5 GSV scores for Symbolic numerical skills, which does not support either of the hypotheses in terms of symbolic numerical skills.

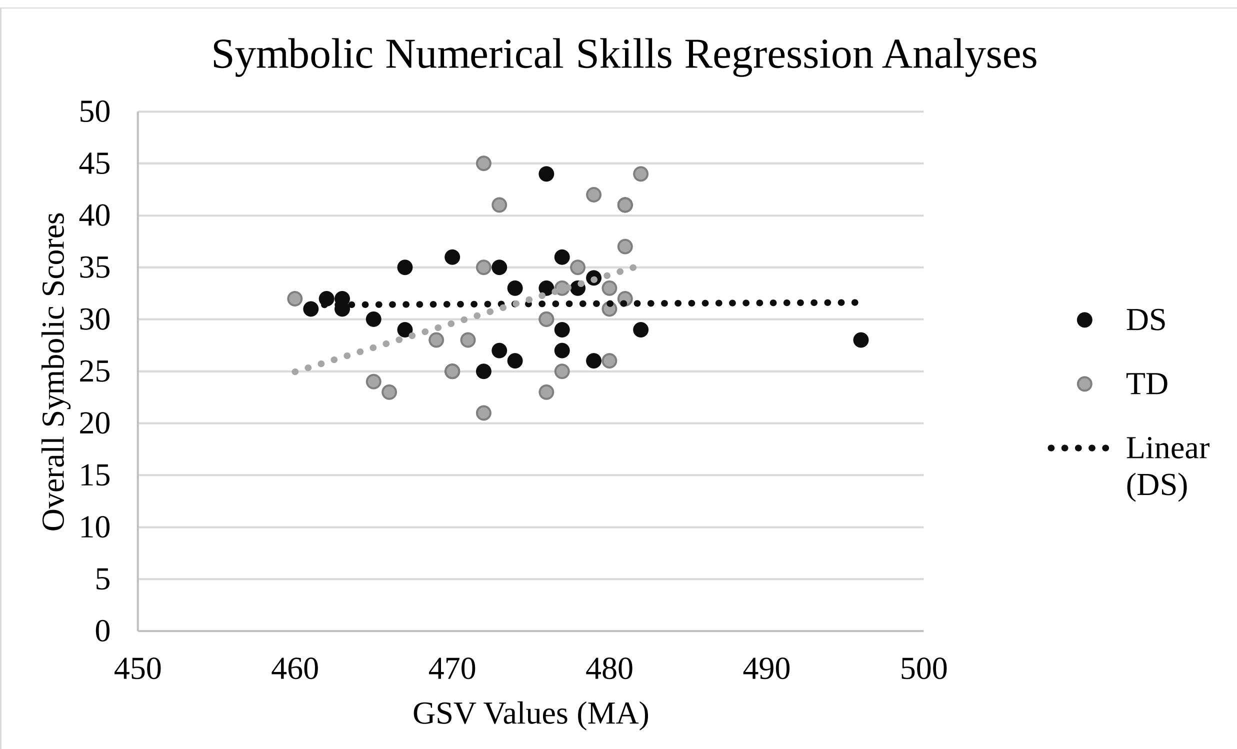

Figure 2. Overall Symbolic Scores over PPVT-5 GSV Scores

Conclusion. Overall, the participants with DS performed similarly to the TD participants across the numerical skills measures for both non-symbolic and symbolic numerical skills. From the first analysis, it can be concluded that participants with DS showed similar levels of numerical skills for both non-symbolic and symbolic numerical skills compared to TD peers matched by MA, but the first analysis just examined group means and whether differences existed. To expand on differences in numerical skills in children with DS, the second and third analyses examined groups on across the range of verbal ability for both foundational numerical skills relative to PPVT-5 GSV scores. It can be argued from these two regressions analyses that individuals with DS perform and develop along a similar trajectory relative to their receptive vocabulary skills score for both non-symbolic and symbolic numerical skills.

4. DISCUSSION

The purpose of the current study was to examine the difference between children with DS and TD peers matched by PPVT-5 GSV scores on two foundational numerical skills. Non-symbolic and symbolic numerical skills were both examined to compare differences between the groups for both ANS and Symbolic Numerical Skills across PPVT-5 GSV scores. Non-symbolic skills were hypothesized to be at a similar level for ANS between the two groups at onset, as well as across PPVT-5 GSV scores. The results supported the hypotheses regarding non-symbolic numerical skills. This means that the results showed that for ANS, not only are individuals with DS performing at a similar level when compared to TD individuals matched by PPVT-5 GSV scores, individuals with DS are performing along a similar slope compared to TD individuals matched by PPVT-5 GSV scores. These results support the idea that non-symbolic numerical skills are a relative strength in children with DS, which is consistent with the findings from Sella et al. (2013), Camos (2009), and Abreu-Mendoza and Arias-Trejo (2015).

Symbolic numerical skills were hypothesized to significantly vary between the two groups at onset, as well as across PPVT-5 GSV scores. More specifically, it was predicted that at onset individuals with DS would perform at a lower level of symbolic numerical skills compared to their MA-matched TD peers. However, the results revealed this was not the case. The DS group did not significantly differ from their TD peers at onset. This finding is consistent with previous literature that suggests that individuals with DS perform at or below their MA-matched TD peers on symbolic numerical skills (Caycho et al., 1991, Sella et al, 2013, Abreu-Mendoza &

Arias-Trejo, 2017). It was also predicted that the MA-matched TD peers would perform along a significantly steeper slope compared to individuals with DS. However, this was also not the case, as there was no significant difference in the slopes between groups. This result is not consistent with the previous literature that argues that individuals with DS perform below TD peers (Abdelahmeed, 2007, and Brigstocke, Hulme, and Nye, 2008, King et al., 2017). Overall, these results did not support the second hypothesis, nor the theory that individuals with DS have a deficit in symbolic numerical skills.

While the second set of regressions did not reveal a significant relationship, it is important to note that both the of the differences in intercept and the differences in slope are approaching significance. This is important to identify because of how many participants had to be removed from the analyses in order to obtain equally matched groups on their receptive vocabulary skills. The power analyses that were performed prior to beginning data collection did reveal that 22 participants in each group was the minimum needed to obtain a power of 0.80 for all three analyses, which is why the number of participants excluded was deemed acceptable. However, the sample size is still small, which could mean that the sample size is not large enough to be able to fully detect the differences between the groups on their symbolic numerical skills. Adding in more participants would allow for more power and possibly reveal that there is a significant difference in both the intercepts and the slopes between the group with DS and the TD group matched by MA for symbolic skills across receptive vocabulary skills. Future studies should aim to have larger sample sizes in both the group with DS and the matched TD group to better understand if there is a significant difference in symbolic skills across receptive vocabulary skills and the sample size here was just too small to be able to detect those differences.

The regression analyses allowed researchers to examine the difference in both non-symbolic and symbolic numerical skills in children with DS beyond just one time point over a simple comparison of means. In the examination of the regression analyses for non-symbolic numerical skills, one can see that the group comparison for non-symbolic numerical skills depends on PPVT-5 GSV scores, or more simply receptive vocabulary skills. However, in the examination of the regression analyses receptive vocabulary skills were not predictive of symbolic numerical skills, which suggests that alternative measures of cognitive ability should be used in future studies to examine the relationship between MA and symbolic numerical skills. It is also possible that the small sample size of the current study was not large enough for the relationship to be detected here, so as well as exploring alternative measures of MA future studies should use PPVT-5 GSV scores with larger sample sizes to know whether lack of power was the reason the relationship was not detected here or if PPVT-5 GSV scores really is not a good measure of cognitive ability when examining symbolic numerical skills.

The current findings support the theory that non-symbolic numerical skills are a relative strength in DS, and also suggest that symbolic numerical skills may not be a challenge in individuals with DS. They also add to current knowledge on the development of numerical skills in children with DS because of the regression analyses. The regression analyses allow researchers examine these numerical skills across different levels of receptive vocabulary skills instead of just an average level of cognitive ability like most previous studies have done.

Practical implications of the current study are important to consider. The more that is understood about the development of numerical skills in individuals with DS, then the better interventions and teaching methods researchers, clinicians, and educators can develop to help improve their numerical skills. If the relative strength of non-symbolic numerical skills in individuals with DS is confirmed with further research, then interventions and teaching methods that focus on the use of non-symbolic numerical skills could be developed to help individuals with DS better develop and master numerical skills and in turn increase their everyday functioning and quality of life.

a. Limitations and Future Directions

These findings support the argument that non-symbolic numerical skills may be relative strengths and symbolic numerical skills may not truly be deficits in individuals with DS when compared to TD individuals on cognitive ability. However, the current study is limited on the argument for symbolic numerical measures and more advanced symbolic numerical skills because it only examined two types of numerical skills. Future studies should attempt to replicate the results with more measures of symbolic numerical skills included in the study to be able to better compare symbolic and non-symbolic measures of numerical skills in individuals with DS. If further comparisons of symbolic and non-symbolic numerical skills are examined, then researchers could determine which measures of numerical skills are optimal for individuals with DS, as well as further examine whether all symbolic numerical skills or specific symbolic numerical skills are deficits in individuals with DS. It would also be beneficial to replicate the results with a larger sample to get a better picture about whether or not non-symbolic numerical skills are truly a relative strength in individuals with DS, and whether symbolic numerical skills are truly no different in children with DS than in their MA-matched peers.

Another limitation to the current study is that the current study was completed via remote testing, which may have yielded different results than in-person testing would have. One possible reason remote testing may have yielded different results than in-person testing is the external distractions that are consistent with reasons that in-home/field testing can yield different results than in-lab testing. Researchers cannot control these external factors, such as other people in the background. Another possible reason remote testing may have yielded different results than in-person testing is that the measures were presented via webcam, so while they were administered properly it is possible that viewing the stimuli via webcam verse in-person may have altered the way participants saw the stimuli. Future studies should repeat the current study virtually and in-person to compare whether remote testing yields similar results. If remote testing and in-person yield the same results, then the possibility for completing studies with individuals with DS remotely could open doors for larger sample sizes and more studies in a shorter time frame, as well as decrease costs of research. While the study being a remote study is a limitation, it is also a strength of the current study because it opens the door for alternative methods of research being explored in this special community.

Future studies should also examine the relationship between reading skills and numerical skills because these may help identify where verbal skills may come into play in numerical skills in children with DS. The current study aimed to examine letter and word identification and its relation to numerical skills but were unable to complete a comparison due to ceiling effect in letter identification and floor effect in word identification. It would be beneficial to examine reading skills in relation to numerical skills, so future studies should explore that relationship using a range of reading measures.

b. Conclusion

The current study has its limitations, but it is an important contribution to DS research because it is one of the first studies to remotely test individuals with DS, as well as the contributions to knowledge of numerical skills in individuals with DS. The above study supports the idea that remote research may be accurate and a viable research method in certain areas of research on individuals with DS.

The current study, also, is one the first studies of the researchers' knowledge to examine the relation of numerical skills to receptive vocabulary skills in individuals with DS vs TD controls. This provides evidence and support for the theory of non-symbolic and symbolic numerical skills as possible relative strengths in individuals with DS, which if they truly are relative strengths, then these two foundational numerical skills may not be a deficit in individuals with DS. As further information is found on how individuals with DS develop numerical skills, interventions, and alternative methods of teaching numerical skills in individuals with DS can be explored. Overall, the current study supports the idea that at least non-symbolic and possibly verbal magnitudes related numerical skills are possible relative strengths in individuals with DS.

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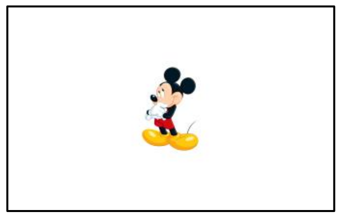
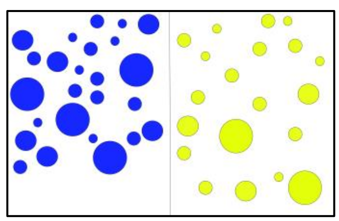
APPENDIX A: EXAMPLES OF ANS NUMBER ACUITY TASK

The steps for all the trials for the ANS Number Acuity Task are as follows:

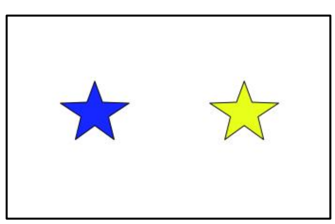
Step 1: Participant is shown the attention screen and asked to look directly at Mickey Mouse.



Step 2: Once the researcher has confirmed that the participant is looking directly at Mickey Mouse, then they begin the trial by pressing the "Space Bar" and an array of blue and yellow dots appear for 2000ms.



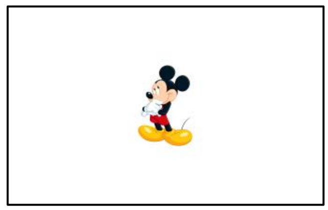
Step 3: After 2000ms has passed, the dots disappear, and the blue and yellow stars appear. Once the stars appear on the screen, the researcher has the participant point to the color that had the most dots, then verbally tell the researcher the color they are pointing to.



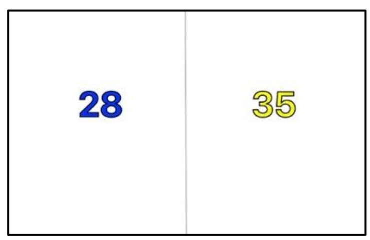
APPENDIX B: EXAMPLES OF SYMBOLIC NUMERICAL SKILLS TASK

The steps for all the trials for the ANS Number Acuity Task are as follows:

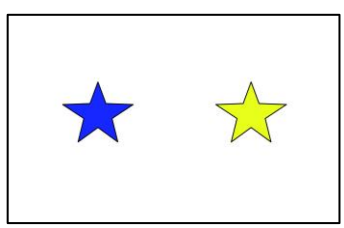
Step 1: Participant is shown the attention screen and asked to look directly at Mickey Mouse.



Step 2: Once the researcher has confirmed that the participant is looking directly at Mickey Mouse, then they begin the trial by pressing the "Space Bar" and a blue Arabic number and a yellow Arabic number appear on the screen for 2000ms.



Step 3: After 2000ms has passed, the numbers disappear, and the blue and yellow stars appear. Once the stars appear on the screen, the researcher has the participant point to the color that had the larger number, then verbally tell the researcher the color they are pointing to.



APPENDIX C: VALIDITY TRACKER EXAMPLE

Task Validity Tracker

Based on Hessl T-PAL NIHtB-CB Administration Form (v1.0, 8/6/19)

Participant ID:	Examiner:

Order & Date	Test	Passed Practice?	Test Valid?	Reasons Invalid or Unsure	Notes
	PPVT-5	Y N NA	Y N ?	☐ Excessive prompting ☐ Examinee refused ☐ Invalid patterned response ☐ Technical difficulties ☐ Illness/emergency ☐ Other Please describe any selections above: _____ _____ _____	☐ Questionable understanding of task (describe below) Other notes: _____ _____ _____ _____ _____ _____ _____
	Numerical Knowledeg Check	Y N NA	Y N ?	☐ Excessive prompting ☐ Examinee refused ☐ Invalid patterned response ☐ Technical difficulties ☐ Illness/emergency ☐ Other Please describe any selections above: _____ _____ _____	☐ Questionable understanding of task (describe below) Other notes: _____ _____ _____ _____ _____ _____ _____
	Symbolic Task	Y N NA	Y N ?	☐ Excessive prompting ☐ Examinee refused ☐ Invalid patterned response ☐ Technical difficulties ☐ Illness/emergency ☐ Other Please describe any selections above: _____ _____ _____	☐ Questionable understanding of task (describe below) Other notes: _____ _____ _____ _____ _____ _____ _____
	Dots Task	Y N NA	Y N ?	☐ Excessive prompting ☐ Examinee refused ☐ Invalid patterned response ☐ Technical difficulties ☐ Illness/emergency ☐ Other Please describe any selections above: _____ _____ _____	☐ Questionable understanding of task (describe below) Other notes: _____ _____ _____ _____ _____ _____ _____

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APPENDIX D: IRB APPROVAL LETTER

THE UNIVERSITY OF ALABAMA | Office of the Vice President for Research & Economic Development
Office for Research Compliance

October 13, 2020

Kristina Baggett
Department of Psychology
College of Arts & Sciences
Box 870348

Re: IRB Application #: 19-018-R1 (e-Protocol 19-07-2502) "Foundational Numerical Skills in Children with DS"

Dear Ms. Baggett:

The University of Alabama Institutional Review Board has granted approval for your proposed research. Your application has been given approval according to 45 CFR part 46.

The approval for your application will lapse on September 16, 2021. If your research will continue beyond this date, please submit the Continuing Review to the IRB as required by University policy before the lapse. Please note, any modifications made in research design, methodology, or procedures must be submitted to and approved by the IRB before implementation. Please submit a final report form when the study is complete.

Please use reproductions of the IRB approved informed consent/assent form to obtain consent from your participants.

Good luck with your research.

Jessup Building | Box 870127 | Tuscaloosa, AL 35487-0127
205-348-8461 | Fax 205-348-7189 | Toll Free 1-877-820-3066