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LEARNING CHANNELS

Investigating the relationship between learning channel sets during the mathematical practice of autistic students

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Learning channels refer to the way students receive instruction and respond to it. We examined the relationship between See-Say and See-Write learning channel sets during the mathematical practice of four male autistic students, aged 8 to 14 years. Participants received practice in the ×7 and ×8 tables across both channel sets. Lessons included untimed practice, timed practice, graphing and goal-setting. A multiple treatments design, embedded in a multiple baseline across participants design, was used. When practice on a set was completed, an assessment of endurance, stability, application, generalisation to the other set and maintenance was conducted. Practice led to improvements that were maintained. Participants achieved learning rates above 30% per week, which is a minimum expectation in Precision Teaching. Practice on one set affected performance on the other, and the order of practice was an important variable. The See-Say channel set led to better generalisation outcomes while performance was stronger on the See-Write.

Key words: **standard celeration chart, special education, Precision Teaching, RESA, fluency**

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Introduction

Precision Teaching is a measurement system that has been primarily applied to mainstream and special education (for a review of its application, see Gist & Bulla, 2020; McTiernan et al., 2021; Ramey et al., 2016). It focuses on developing behavioural repertoires while precisely analysing behaviour change across time through a five-step framework defined as 'pinpoint', 'practice', 'chart', 'decide' and 'try again' (Evans et al., 2021). In the pinpoint phase, the practitioner defines the behaviour by using movement cycles and learning channels. In the practice phase, they arrange instruction that promotes the acceleration of behavioural repertoires. In the charting phase, they use dimensional measures of behaviour, such as frequency, and a family of graphical displays, known as the Standard Celeration Charts (Calkin, 2005). In the decide phase, they evaluate the outcomes and engage in problem-solving, if necessary. Finally, in the try again phase, they apply the strategies identified via problem-solving and recursively evaluate them (Evans et al., 2021).

Along with its framework, Precision Teaching incorporates strategies that are not essential but are typically combined with it. For example, *frequency building to a performance criterion* (or simply fluency training), defined as timed practice and performance feedback, is used to develop fluent skills (Binder, 1996; Kubina & Yurich, 2012).

Among all the elements of Precision Teaching, one that has received minimal attention is *learning channels* (Haughton, 1980; Kubina & Yurich, 2012; Lindsley, 1998). By learning channels, we refer to the sensory modality of the three-term contingency's first two components (that is, antecedent–behaviour–postcedent). Specifically, precision teachers pinpoint the way(s) individuals come in contact with antecedent events, which they call the *sensory Ins*, and how they subsequently respond to them, which they call *behavioural Outs* (Kubina & Yurich, 2012). For example, if a student is presented with a math fact and writes the answer to it, the *learning channel set* would be See-Write, because the student would See the math fact and respond to it in Writing.

Early research on learning channels has provided intriguing results. Lindsley (1990) suggested that learning channels are independent of each other. For instance, a person could perform fluently on See-Say but perform poorly on Hear-Write on the same task. The early research also led Lindsley (1998) to suggest that 'the channel on which someone performs best at is not necessarily the channel they learn best in'. In other words, students practising a skill

might perform better on one learning channel but learn faster on a different channel. Furthermore, Lindsley (1998) also suggested using the strongest learning channel to train less developed ones on the same task. Despite the early findings, there has been insufficient research to support these claims or extend the knowledge base around learning channels. Learning channels have been used in research (Lin & Kubina, 2000), and recommendations about their use have been made (Nam & Spruill, 2005), but there have only been two recent peer-reviewed studies on the relationship between learning channel sets (Nam & Spruill, 2005; Zanatta & Rosales-Ruiz, 2021).

Nam and Spruill (2005) evaluated the See-Say, Hear-Say and See-Write learning channel sets during Math training in a special education setting. A multiple treatments design was used to target the multiplication tables of ×3, ×4, ×5 and ×6. The results suggested that practice on the See-Say set had no effect on the See-Write set, while practice on the Hear-Say set generalised to the See-Write. In other words, even though participants practised seeing multiplication facts and saying the answer, they did not improve their written performance. Still, they improved their written performance when they practised hearing multiplication facts and saying the answer. However, the authors highlighted the possibility of sequence effects as the design was not counterbalanced.

In a more recent study, Zanatta and Rosales-Ruiz (2021) evaluated the Hear. See-Say and Hear.See-Write learning channel sets and their impact on the See-Say, See-Write, Think-Say, Think-Write and See Name-Draw Symbol sets. Greek letters were taught during the study, which took place in a mainstream education setting. A multiple treatments design was used, where 12 letters were allocated to each set for a total of 24 letters. The results suggested that the Hear. See-Say set produced higher frequencies for all participants and faster learning rates (that is, celerations) for three out of four participants. However, results also suggested that performance was more accurate on the Hear.See-Write, while generalisation and retention were also better on this learning channel set.

Therefore, it is evident that our field has a preliminary understanding of the topic, necessitating more research on the relationship between learning channel sets. To that end, this study used a multiple treatments design embedded in a multiple baseline across participants design to evaluate the relation between the See-Say and See-Write sets. The multiplication tables of ×7 and ×8 were targeted through the use of a Precision Teaching framework that included untimed and timed practice, graphing and goal-setting.

The study addressed the following research questions:

1. whether improvements in one learning channel set will generalise to another without direct training;
2. whether performance (that is, frequency) and learning (that is, celeration) across learning channel sets are different;
3. whether the practice sequence of learning channel sets affects student outcomes.

Methods

Participants, inclusion criteria and setting

Six Caucasian male autistic students, with English as their first language, were assessed for participation, and four were included. All came from special schools within England. Jordan (pseudonym) was eight years old, Caleb and Kieran were 12, and Roger was 14. Kieran and Roger were also diagnosed with attention deficit hyperactivity disorder, as specified in the local authority's Education, Health and Care Plan. None of the students had a diagnosis of an intellectual disability.

To participate, students needed to (a) have a diagnosis of a developmental disability, (b) be vocal, (c) be able to complete the first 50 items on the Test of Early Mathematics Ability-3 (TEMA-3; Ginsburg & Baroody, 2003), (d) have at least one week of lessons on addition, subtraction, multiplication and division, and (e) not be exhibiting behaviours described as challenging that would interfere with the study's procedures. Out of the six students, two were excluded due to their performance on the TEMA-3.

This study received a favourable ethical opinion from the ethics committee of the University of Kent. Children were invited and agreed to take part in this study after parental consent for their inclusion had been obtained.

Learning channel sets and multiplication tables

Multiplication was taught across both learning channel sets. Four multiplication tables were originally assessed, namely ×6, ×7, ×8 and ×9, for five days. The ×7 and ×8 tables were ultimately chosen due to having the same number of digits and being, on average, the tables with the weakest performance across all participants.

Response definitions and data collection

The multiplication skills were pinpointed as (a) See-Says number of (×7/×8) multiplication fact presented randomly on the worksheet and (b) See-Writes number of (×7/×8) multiplication fact presented randomly on the worksheet. Data were collected on correct and incorrect vocal responses per minute for See-Say and on correct and incorrect written digits per minute for See-Write. The tables were divided into two subsets (also known as slices) to make practice accessible. Subset 1 included combinations ×2 to ×6 (for example, 7 × 2 =) and subset 2 included ×7 to ×11 (for example, 8 × 11 =). The entire set included all combinations from ×2 to ×11.

Materials

Assessment tools

Along with the TEMA-3, three standardised assessments were used to provide more information about the participants' mathematical ability, adaptive behaviour, and autistic traits (see tables 1 and 2). The tools used were the Test of Mathematical Abilities–3rd Edition (TOMA-3; Brown et al., 2013), the Vineland Adaptive Behaviour Scales–II Teacher Rating Form (VABS-II TRF; Sparrow et al., 2005) and the Gilliam Autism Rating Scale–2nd Edition (GARS-2; Gilliam, 2006).

General classroom materials

A4 ring binders were used to store the worksheets. Two non-standardised line graphs, a timings graph and a daily graph were also constructed. The timings graph had an x-axis divided into five days, and each day was divided into five timings. The daily graph had an x-axis that included weekdays

Table 1: Data from the assessment tools

Participants	TEMA-3	TOMA-3	VABS-II TRF	GARS-2
	Raw scores	Maths ability index	Composite score	Autism index
Jordan	66	106	94	81
Caleb	62	81	102	45
Kieran	58	81	77	59
Roger	67	86	99	51

Notes: TEMA-3: Test of Early Mathematical Ability–3rd edition; TOMA-3: Test of Mathematical Abilities–3rd edition; VABS-II TRF: Vineland Adaptive Behaviour Scales-II Teacher Rating Form; GARS-2= Gilliam Autism Rating Scale–2nd edition. Standard Score on VABS-II excludes the motor domain. TEMA raw scores are reported as participants were above the age range of administration.

Table 2: Overview of the assessment tools

Name	Domains assessed	Standardisation[a]	Duration of administration[b]
TEMA-3[c]	1. Counting proficiency 2. Cardinality 3. Number comparison facility 4. Elementary arithmetic	Internal consistency 0.94–0.96 Test-retest reliability 0.82–0.93	40min
TOMA-3	1. Mathematical symbols and concepts 2. Computation 3. Mathematics in everyday life 4. Word problems 5. Attitude towards maths (supplemental)	Internal consistency at 0.96 Test-retest reliability at 0.89	90min
VABS-II TRF	1. Communication 2. Daily living skills 3. Socialisation 4. Motor skills	Internal consistency at 0.98 Test-retest reliability at 0.91	20min
GARS-2	1. Stereotyped behaviours 2. Communication 3. Social interaction	Internal consistency at 0.94 Test-retest reliability at 0.88	10min

Notes: TEMA-3: Test of Early Mathematical Ability–3rd edition; TOMA-3: Test of Mathematical Abilities–3rd edition; VABS-II TRF: Vineland Adaptive Behaviour Scales-II Teacher Rating Form; GARS-2= Gilliam Autism Rating Scale–2nd edition.

[a]Coefficient alphas are reported.

[b]The average duration is reported.

[c]The results are reported for Forms A and B respectively.

(that is, Monday to Friday) for a total of 20 days. Practice sessions were conducted daily, and each session's data were plotted on a separate day line on the daily graph. Practice sessions took place in a 3m x 3m room, equipped with a camera, a whiteboard, a desk, two chairs and two storage cupboards with all the necessary resources. Both graphs had a logarithmic scale on the y-axis. Pencils, erasers, notebooks and digital timers were used. An A4 laminated class-shop catalogue was created with pages in portrait orientation and a 28-point Times New Roman font with a picture in the middle of each page (sized 13 × 15 cm) showing each available item. Finally, a points board was made in portrait orientation with a 12-point Times New Roman font and a 6 × 6 grid.

Materials and worksheets for mathematical practice

Flashcards sized 3 x 5 inches were created for ×7 and ×8 tables. A multiplication fact (such as, 3 × 5 =) was at the front of the card, with the answer at the back (for example, 15) in an 18-point Arial font. Also, A4 worksheets were created for each learning channel set, with 10 horizontal multiplication facts per page, presented in random order, in a 20-point Arial font and for a total of 35 pages. The combinations ranged from 7 × 2 = to 7 × 11 = or 8 × 2 = to 8 × 11 = depending on the learning channel set and the subset practised. Counterparts, including the answers, were created for the teacher to score during See-Say practice. All worksheets were created using Microsoft Excel™ and Microsoft Word™ and were randomised and unique to each participant. Finally, for the assessment of application, A4 worksheets with 25 facts per page, aligned vertically, and for a total of 10 pages, were created via the website www.math-aids.com. All worksheets had additional pages to avoid artificial ceilings on performance.

Research design

A multiple treatments design embedded in a multiple baseline across participants design was utilised. The design involved a baseline condition (A1) that lasted at least five days, a practice condition on one learning channel set (B or C), then a mastery assessment (A2), a practice condition on the other learning channel set (B or C), and again a mastery assessment (A3). Thus, the design was either A1-B-A2-C-A3 or A1-C-A2-B-A3. Each sequence was assigned to one of the two multiplication tables, enabling participants to practice both sequences. The sequences were randomly allocated to participants through an online dice roller (https://www.random.org/dice/). The allocation was counterbalanced across participants so that there would always be two participants receiving the same sequence.

Procedure

The baseline assessments, daily practice sessions and mastery tests (see Figure 1) were conducted by the first author, who is a qualified teacher and a board-certified behaviour analyst (BCBA).

Baseline

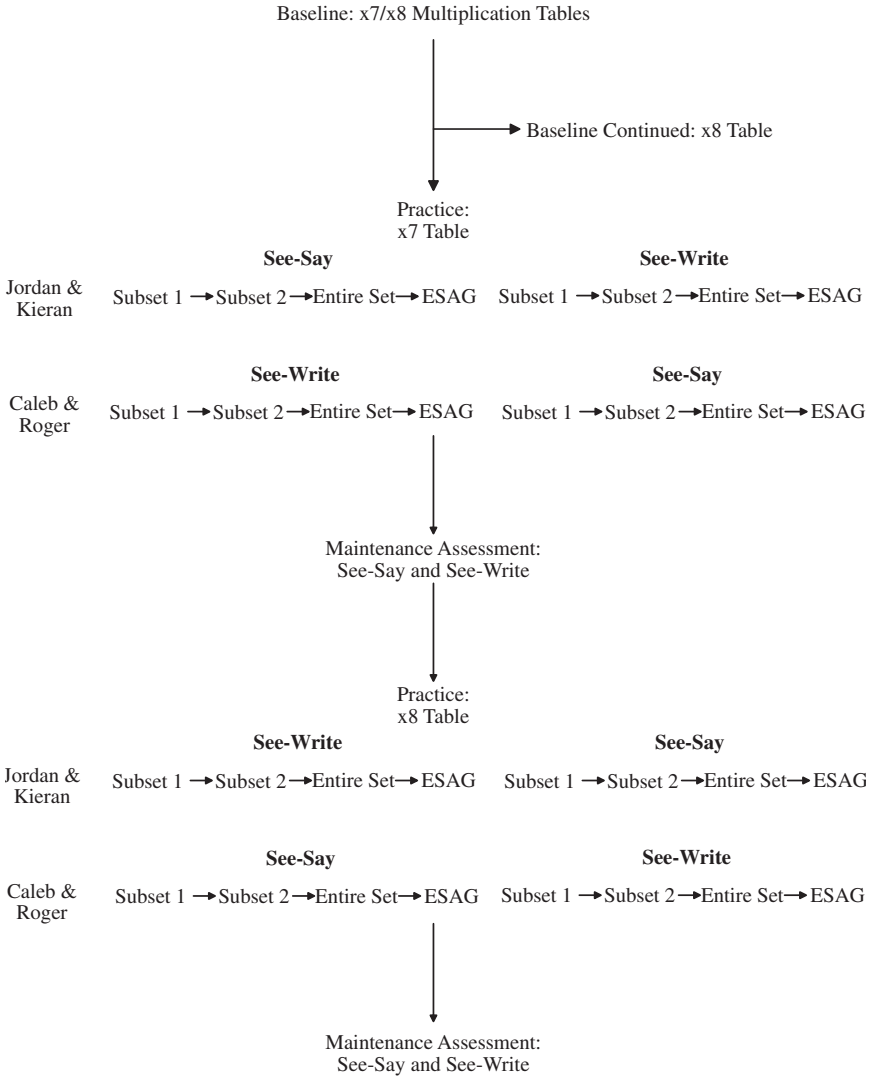
Baseline data were collected on a 1:1 teacher-to-student ratio and included a 30-second timing without any practice, graphing, feedback or token economy, and five minutes of playtime for participating in the session.

Practice on multiplication

Participants practised one learning channel set at a time. They were first introduced to the ×7 multiplication table and then ×8 (see Figure 1). Practice on each learning channel set was daily for a total of three school weeks, with an average duration of 12 minutes (range: 7–17 minutes). Participants were introduced to the ×8 table only after practising both sets on ×7.

At the beginning of the week, they engaged in a set-criterion timing. This timing included no feedback and allowed us to set the day's performance criterion by increasing their score by one correct vocal response or written digit in line with the personal best approach (Ginns et al., 2018). Once the criterion was set, participants engaged in untimed practice that included a pack of 20 flashcards. During this practice, they would look at the front of each flashcard, say or write the response, depending on the learning channel set, and then flip the card to see the answer. Once they worked through all 20 cards once, they would engage in a 30-second timing using the relevant worksheet and repeat the process for a maximum of five 30-second timings. In this way, participants built up their fluency. If participants reached their daily criterion on the first timing, practice on that skill was completed for the day, and the criterion was increased by one for the next day's practice. If they did not meet their daily criterion after five timings, it remained the same for the next day. To receive ongoing visual feedback during the practice session and across the week, participants graphed their performance after each timing on the timings graph and their best score of the day on the daily graph. To keep their motivation high, they also received points on a Variable Ratio of 3 schedule throughout the lesson for engaging in all aspects of practice that they exchanged at the end for five minutes of playtime with a preferred item available in the class shop catalogue. The price of the items varied, but participants needed a minimum number of points to access the catalogue.

Figure 1: A sequence diagram of the study's steps. *Note*: ESAG = Endurance, Stability, Application, Generalisation



Assessment of mastery and generalisation across learning channel sets

Once practice on a learning channel set was completed, we delivered a mastery test of *endurance, stability, application, generalisation* to the other set

and *maintenance* (ESAG-M) following the guidelines by Fabrizio and Moors (2003). The ESAG-M test is also known by other acronyms, such as REAPS or RESAA (Johnson & Layng, 1996), and its components are considered fluency indicators (Fabrizio & Moors, 2003). ESAG was conducted on each learning channel set's final day of training to evaluate whether performance improvements would be maintained under different conditions. First, we assessed endurance by conducting a timing three times longer than usual (that is, 90 seconds). Second, we assessed stability by playing music while saying random numbers to the participants during a 30-second timing. Third, to evaluate performance in a novel situation, we assessed application by asking participants to use a novel worksheet to engage in a 30-second timing. Fourth, we assessed generalisation by asking participants to perform a 30-second timing on the other learning channel set. Finally, we assessed maintenance by asking participants to engage in one 30-second timing for each set, once a week for five consecutive weeks.

Absence protocol

If participants missed one or two days of practice, they engaged in one or two double sessions accordingly (for example, morning and afternoon). If participants missed three days of school, they restarted their weekly practice. The protocol was implemented twice with Kieran, on subset 2 of See-Write ×7, and the entire set of See-Say ×8, and once with Caleb on the entire set of See-Write ×8.

Performance criteria

As performance varies across individuals, a range of frequencies was set as each skill's ultimate performance criterion, in line with the Precision Teaching literature (Johnson & Street, 2013; Kubina & Yurich, 2012). See-Say's criterion was 90–110 correct vocal responses per minute, while for See-Write, it was 80–100 correct written digits per minute. The range plotted on the graphs allowed participants to evaluate their progress.

Data analysis

Data were plotted on Standard Celeration Charts using the online software PrecisionX (CentralReach, 2019). The level was calculated, through the geometric mean, for each phase of the study based on the participants' best score of each day. The geometric mean regulates the data collected, so one set of numbers does not have more weight than another set of numbers and is less affected by extreme variables (Clark-Carter, 2005; Wertalik & Kubina, 2018). Celeration (that is, (count/unit of time)/unit of time) quantifies learning rate

across time. The frequency multiplier (that is, highest frequency ÷ lowest frequency) calculates the ratio of change between two data points. For all the ratios calculated, the multiplication (x) or division (÷) sign was affixed to indicate an increase or decrease of performance across time or between data points (Kubina & Yurich, 2012). For example, a ×2 weekly celeration increase would indicate an increase of 100% per week. Similarly, a ÷ 2 multiplier would suggest a 50% reduction between two data points. For ease of interpretation, all ratios were transformed into percentages.

Although a visual analysis of graphed data characterises single-case designs, it is considered good practice to calculate effect sizes to assess autocorrelation or baseline trends and quantify the direction and magnitude of the intervention's effect (Campbell, 2004; Parker et al., 2011). First, the Non-Overlap of All Pairs (NAP) was used, which is highly correlated with the R^2 effect size index (Parker & Vannest, 2009; Vannest et al., 2016). It also produces effect size magnitudes comparable with other overlap indices (Ma, 2006; Parker et al., 2007; Scruggs et al., 1987). Second, the Baseline Corrected Tau was calculated due to ascending baseline trends for correct responses/digits. This effect size evaluates whether there is a monotonic trend in the baseline and corrects it if necessary (Tarlow, 2016, 2017). Weak effects were between 0 and 0.65, moderate effects were between 0.66 and 0.92, and strong effects were between 0.93 and 1.0. Finally, to evaluate the outcome's statistical significance, bootstrapping with 5,000 samples with replacement was utilised (http://www.clinicalresearcher.org/software.htm). All calculations compared performance between baseline and maintenance conditions.

Inter-observer agreement

Inter-observer agreement (IOA) was calculated, by an independent BCBA, for an average of 38.5% (range: 35% to 41.5%) of randomly selected sessions for all participants. IOA was calculated separately for correct and incorrect responses and then combined to form a single mean for baseline, practice and maintenance phases. The overall mean IOA was then calculated across all multiplication tables. Agreement was 100% for Jordan, 99% (range: 97% to 100%) for Caleb, 98% (range: 95% to 100%) for Kieran, and 99% (range: 96% to 100%) for Roger.

Procedural fidelity

A separate checklist was created for the baseline, practice and maintenance conditions (available upon request). Baseline and maintenance checklists included the same 10 items, while the practice checklist included 14 items that

were rated for their presence or absence. The same independent BCBA scored fidelity data for the same percentage of sessions. Procedural fidelity was 96% (range: 91% to 100%) for Jordan and 97% (range: 91% to 100%) for the other three participants.

Social validity

At the end of the study, participants were provided with a questionnaire we developed that included 26 open-ended questions about different aspects of their training, such as the use of graphs and the different learning channel sets. There were three types of questions. Some included a happy or unhappy face underneath, others a set of possible answers, while others had a blank space for participants to write in. Participants read each question aloud and answered it accordingly depending on the question's format.

Results

Multiplication tables ×7 and ×8

The results will follow each participant's order of practice. With the exception of Kieran on See-Write ×7 ($r = 0.36$, $p = 0.209$), all participants made significant improvements, with moderate to high NAP effect sizes (see Figures 2 and 3). However, due to ascending baseline trends, we also calculated the Baseline Corrected Tau which produced a wider range of results with weak to moderate effect sizes (see table 3). Nevertheless, in all cases, performance on the mastery and maintenance assessments was above baseline levels, and incorrect responses/digits were in most cases zero, while practice on one learning channel set led to improvements on the untrained set (see Figure 4).

Jordan: See-Say ×7, See-Write ×7 and See-Write ×8, See-Say ×8

Jordan's average correct responses on See-Say ×7 were 8/min during baseline, 54/min during practice and 36/min during maintenance (see Figure 2, first panel). His learning (that is, celeration) increased by an average of 89% per week during practice. During the mastery assessment (ESAG), his performance was 39 correct responses/min for endurance, 46/min for stability, 50/min for application and 56 digits/min for generalisation. Jordan's performance increased from baseline to generalisation by 600% (see Figure 4). His correct digits on See-Write ×7 were 17/min, 86/min and 57/min per phase. His learning increased by 29%. His performance on ESAG was 67/min, 80/min, 64/min and 58/min, respectively.

Figure 2: Participants' performance on the ×7 multiplication table. *Note*. Baseline and maintenance data were collected on a weekly basis. Statistical significance and the NAP are presented on the side of the figure. Confidence intervals for the NAP were set at 95%. Endurance, Stability, Application, and the Generalisation probe on the other learning channel set are presented as one condition (ESAG). Each datum point, in the ESAG condition, represents a timing for the relevant test

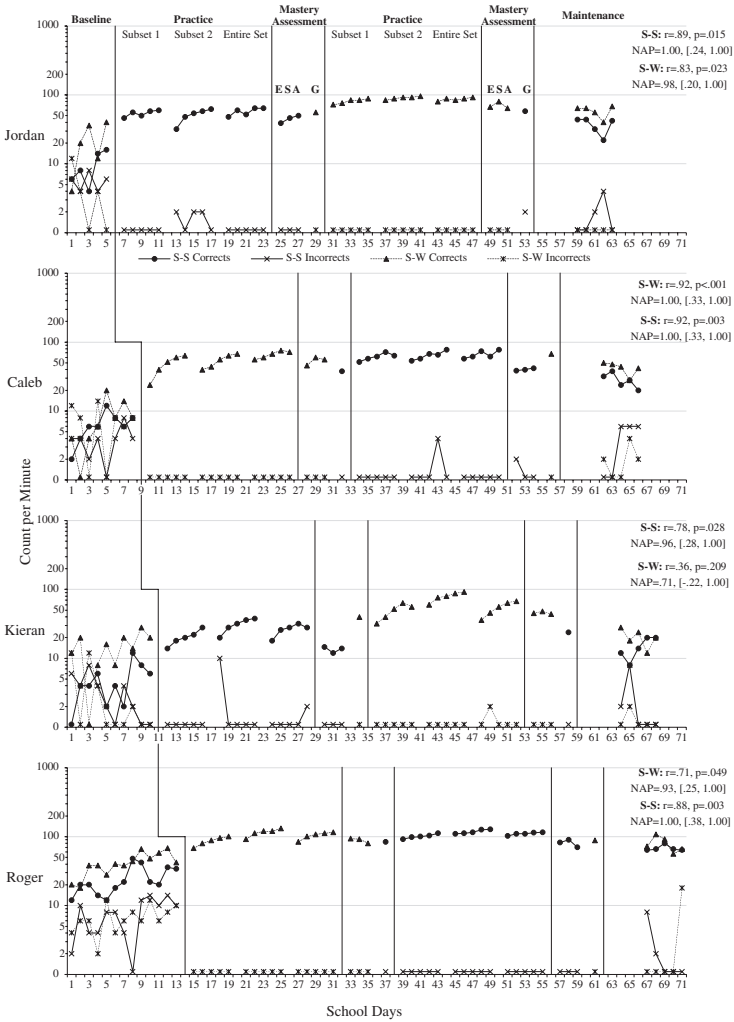


Figure 3: Participants' Performance on the ×8 Multiplication Table. *Note*: We had to swap the participants' order and place Kieran on the last tier for the ×8 multiplication table due to a period of absence from school. Statistical significance and the NAP are presented on the side of the figure. Confidence intervals for the NAP were set at 95%. Endurance, Stability, Application, and the Generalisation probe on the other learning channel set are presented as one condition (ESAG). Each datum point, in the ESAG condition, represents a timing for the relevant test

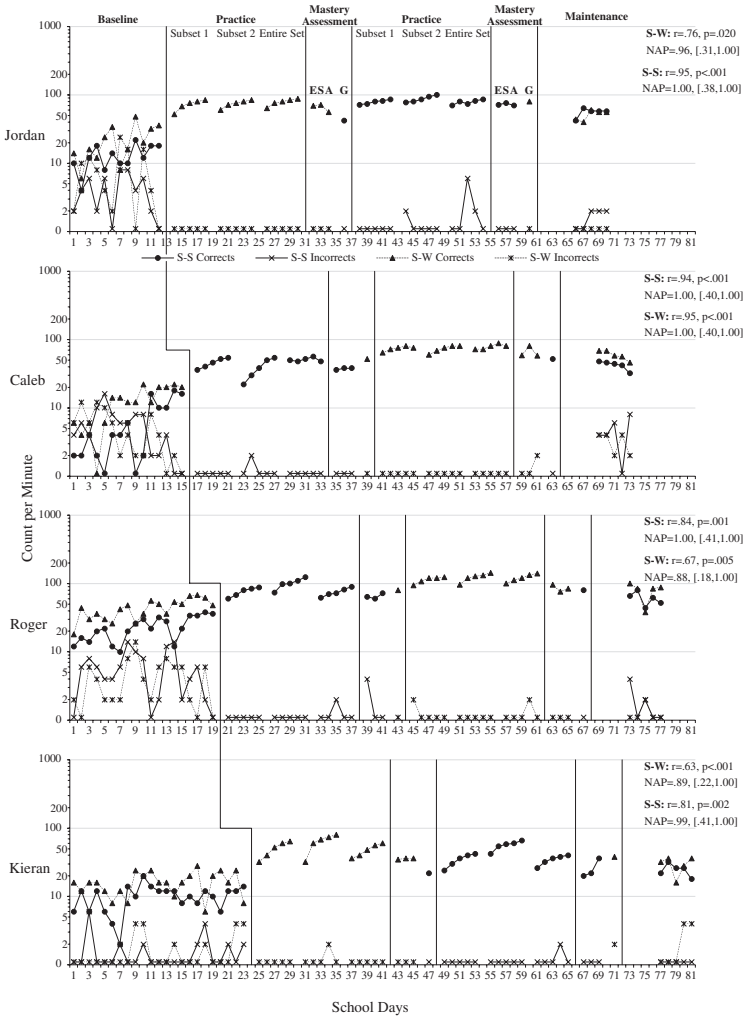


Table 3: Effect size calculated using the Baseline Corrected Tau

Learning channel set	Participants	Baseline Trend	Tau	p	SE_{Tau}
See-Say ×7					
	Jordan	No correction	0.754	0.012	0.294
	Caleb	No correction	0.735	0.004	0.266
	Kieran	No correction	0.661	0.005	0.274
	Roger	Corrected	0.652	0.002	0.253
See-Write ×7					
	Jordan	No correction	0.732	0.016	0.305
	Caleb	No correction	0.725	0.004	0.270
	Kieran	No correction	0.303	0.215	0.348
	Roger	Corrected	0.110	0.622	0.331
See-Say ×8					
	Jordan	No correction	0.690	0.002	0.248
	Caleb	Corrected	0.647	0.001	0.241
	Roger	Corrected	0.564	0.001	0.238
	Kieran	No correction	0.575	0.001	0.219
See-Write ×8					
	Jordan	Corrected	0.421	0.051	0.311
	Caleb	Corrected	0.633	0.001	0.245
	Roger	Corrected	0.340	0.059	0.271
	Kieran	No correction	0.465	0.006	0.237

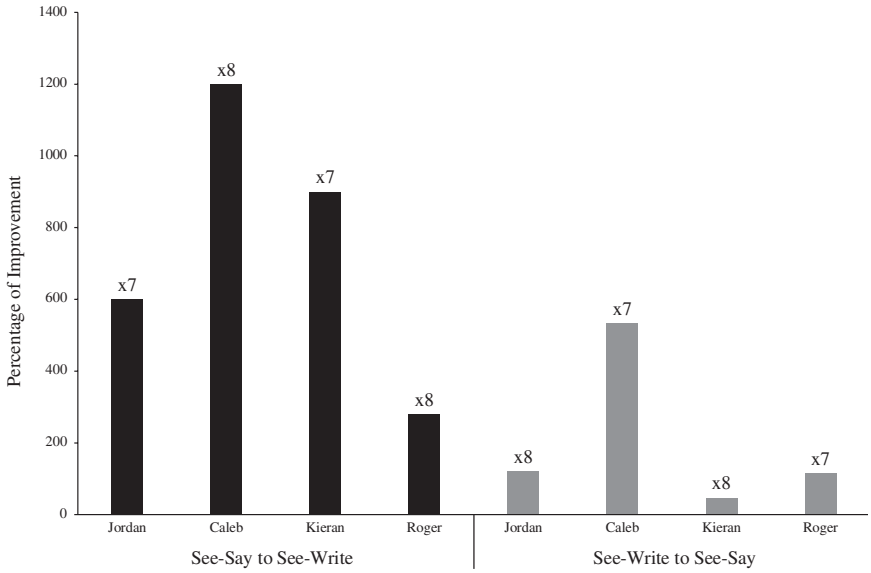
Note: Roger and Kieran were introduced to the ×8 practice in a different order due to school absence.

Jordan's correct digits on See-Write ×8 were 19/min, 74/min and 51/min per phase (see Figure 3, first panel). His learning increased by 85%. His performance on ESAG was 69/min, 72/min, 56/min and 42/min, respectively. Jordan's performance increased from baseline to generalisation by 121% (see Figure 4). Jordan's correct responses on See-Say ×8 were 12/min, 81/min and 55/min per phase. His learning increased by 44%. His performance on ESAG was 72/min, 76/min, 70/min and 80 digits/min, respectively.

Caleb: See-Write ×7, See-Say ×7 and See-Say ×8, See-Write ×8

Caleb's average correct digits on See-Write ×7 were 6/min during baseline, 54/min during practice and 42/min during maintenance (see Figure 2, second panel). His learning increased by an average of 189% during practice. His performance on ESAG was 46/min, 60/min, 56/min and 38/min respectively. Caleb's performance increased from baseline to generalisation by 533% (see Figure 4). His correct responses on See-Say ×7 were 6/min, 64/min and

Figure 4: Participants' Improvement on the Untrained Learning Channel Set. *Note*: The black columns show the amount of improvement produced on the See-Write (untrained) learning channel set, after receiving training on the See-Say. The grey columns show the amount of improvement produced on the See-Say (untrained) learning channel set, after receiving training on the See-Write. The ratios produced by the frequency multiplier were transformed into percentages



28/min per phase. His learning increased by 63%. His performance on ESAG was 39/min, 40/min, 42/min and 68/min respectively.

His correct responses on See-Say ×8 were 4/min, 44/min and 42/min per phase (see Figure 3, second panel). His learning increased by 124%. His performance on ESAG was 36/min, 38/min, 38/min and 52/min respectively. Caleb's performance increased from baseline to generalisation by 1200% (see Figure 4). Caleb's correct digits on See-Write ×8 were 10/min, 74/min and 59/min per phase. His learning increased by 45%. His performance on ESAG was 59/min, 80/min, 58/min and 52/min respectively.

Kieran: See-Say ×7, See-Write ×7 and See-Write ×8, See-Say ×8
Kieran's average correct responses on See-Say ×7 were 4/min during baseline, 25/min during practice and 14/min during maintenance (see Figure 2, third

panel). His learning increased by an average of 168% during practice. His performance on ESAG was 15/min, 12/min, 14/min and 40/min respectively. Kieran's performance increased from baseline to generalisation by 900% (see Figure 4). His correct digits on See-Write ×7 were 11/min, 58/min and 20/min per phase. His learning increased by 166%. His performance on ESAG was 45/min, 48/min, 44/min and 24/min respectively.

His correct digits on See-Write ×8 were 15/min, 51/min and 28/min per phase (see Figure 3, fourth panel). His learning increased by 226%. His performance on ESAG was 35/min, 36/min, 36/min and 22/min respectively. Kieran's performance increased from baseline to generalisation by 47% (see Figure 4). His correct responses on See-Say ×8 were 9/min, 40/min and 24/min per phase. His learning increased by 124%. His performance on ESAG was 20/min, 22/min, 36/min and 38/min respectively.

Roger: See-Write ×7, See-Say ×7 and See-Say ×8, See-Write ×8

Roger's average correct digits on See-Write ×7 were 39/min during baseline, 100/min during practice and 77/min during maintenance (see Figure 2, fourth panel). His learning increased by an average of 79% during practice. His performance on ESAG was 93/min, 92/min, 80/min and 84/min respectively. Roger's performance increased from baseline to generalisation by 115% (see Figure 4). His correct responses on See-Say ×7 were 22/min, 110/min and 68/min per phase. His learning increased by 31%. His performance on ESAG was 82/min, 90/min, 70/min and 88/min respectively.

His correct responses on See-Say ×8 were 21/min, 83/min and 60/min per phase (see Figure 3, third panel). His learning increased by 103%. His performance on ESAG was 64/min, 60/min, 72/min and 80/min respectively. Roger's performance from baseline to generalisation increased by 281% (see Figure 4). Roger's correct digits on See-Write ×8 were 41/min, 119/min and 75/min per phase. His learning increased by 76%. His performance on ESAG was 96/min, 76/min, 84/min and 80/min respectively.

Social validity

All participants reported that they enjoyed having a performance criterion, working at their natural pace and graphing their scores, and indicated that they would like to learn more things this way. All participants indicated a preference for the See-Write set, while agreement on the sequence of sets was divided in half.

Discussion

This study aimed to evaluate: (a) whether improvements in one learning channel set will generalise to another without direct training, (b) whether performance and learning across learning channel sets are different, and (c) whether the learning channel set's sequence of practice might affect student outcomes.

The results are promising as practice led to gains across all skills, with moderate to high NAP effect sizes and solid maintenance of effects, in alignment with the existing literature (McTiernan et al., 2018; Vostanis et al., 2020, 2021). However, the Baseline Corrected Tau calculation highlighted the possibility that increases in baseline performance could have inflated the effect size calculations. Therefore, the reader should interpret the results with caution. Generally, considering the increases in correct performance and the decreases in incorrect performance, it would be safe to conclude that results were positive overall. However, the actual magnitude of the effect is unclear and could potentially be smaller than the data suggest. This fact is particularly important as for Kieran and Roger on See-Write ×7, and Roger on See-Write ×8, corrected effect sizes were non-significant.

The study also produced additional findings. First, it seems that the learning channel sets are related as training on one led to improvements on the other. Second, the See-Say set seems to lead to better generalisation outcomes than the See-Write. Third, there does not seem to be a set that leads to higher learning rates, but the See-Write was stronger in terms of performance. Also, the practice sequence seemed to be important as all participants had a better overall performance on the set they trained on last. As a general suggestion, since generalisation across sets is possible and their sequence could be important, teachers should integrate these findings into their instructional design and activity planning to optimise outcomes.

In terms of the relationship between sets, our results contradict Nam and Spruill's (2005) conclusion that practice on See-Say led to no improvements on the See-Write and Lindsley's (1990) conclusion that learning channels are independent of each other. However, they confirm Zanatta and Rosales-Ruiz's (2021) finding that practice on one learning channel set improved performance on the other. It seems that learning channel sets are interdependent as practice on one set affects performance on the other, while maintaining the potential for further improvement within the untrained set. This was confirmed by the celeration values, which were lower, yet still increasing, on the set that received training last. Thus, educators should not assume that improvements will be the

same across sets and should offer varied instruction (Kubina & Cooper, 2000), a procedure known as *channel wrapping*.

Regarding generalisation across sets, the See-Say was the most effective, contradicting the literature suggesting a weak generalisation from See-Say to See-Write (Nam & Spruill, 2005; Zanatta & Rosales-Ruiz, 2021). However, our findings are in line with Zanatta and Rosales-Ruiz's (2021) suggestion that generalisation might depend on the learning channel sets used and not on performance reaching fluency levels (Binder, 1996; Johnson & Layng, 1996).

Regarding learning, no set consistently produced steeper celerations as the results were equally divided across participants. Considering performance, the data confirm recent evidence (Zanatta & Rosales-Ruiz, 2021) that See-Say is weaker than See-Write as all participants had lower performance on baseline and maintenance, except for Jordan on the ×8 table. However, three of the four participants showed more improvement in See-Say, bearing in mind that their initial performance was lower within this set. This is most likely linked to the verbal reasoning and communication difficulties of students with autism (Sundberg & Michael, 2001), which may explain some of the variance in the outcome. Therefore, teachers should not over-rely on written activities as autistic students can improve their performance on the See-Say channel set despite their communication difficulties.

As for the final aim, performance on the learning channel sets was affected by the practice sequence, a question posed by Nam and Spruill (2005). Participants performed better on either set when they trained on it last. Thus, prior training on a different learning channel set led to improvements on the untrained set and also optimised subsequent performance. Therefore, it confirmed that learning channels are amenable to training (Lindsley, 1998). As a result, educators should consider the sequence of sets during their lesson planning. A beneficial tactic would be to work on a less demanding set that leads to robust generalisation (for example, See-Say) and then practice on the learning channel set on which students will ultimately be assessed.

An additional finding was related to the fluency standards and their relation to the ESAG-M test. Generally, participants did not reach the expected performance criteria. Jordan succeeded in See-Write ×7 and ×8, Caleb in See-Write ×8, and Roger in all four multiplication tables. However, only Roger maintained his performance during the ESAG-M and only for the See-Write. This finding highlights the need for more research on performance criteria

and how they should be set and evaluated, a recommendation also made by Zanatta and Rosales-Ruiz (2021). Historically, the Precision Teaching literature has reported performance criteria either based on the skill (Johnson & Street, 2013; Kubina & Yurich, 2012) or the learning channel set (Fabrizio & Moors, 2003). With both approaches, performance criteria are reported as a range of frequencies, as students performing within that range are more likely to show the by-products of fluent performance (that is, ESAG-M) (Binder, 1996; Haughton, 1980). Our results suggest that performance criteria should be based on the learning channel practised rather than the particular skill, a recommendation also made by Fabrizio and Moors (2003). Therefore, teachers should consider using similar criteria for different activities within the same learning channel set, such as practising phonics or number reading on the See-Say channel set. However, another reason for this result could be cumulative dysfluency on additional prerequisite skills preceding multiplication that were not targeted in this study (McDowell & Keenan, 2001). Cumulative dysfluency refers to students' inability to master new skills or content due to underlying dysfluent skills that make curriculum progression particularly difficult for them (Berg-Mortensen et al., 2021; Kostewicz et al., 2020; McDowell & Keenan, 2001).

Another finding was that participants (except Jordan in one skill) achieved more than the 30% minimum weekly progress across all skills (White & Haring, 1980). Therefore, learning expectations for autistic students could be similar to typically developing students', such as a ×2 (100%) weekly progress (Johnson & Street, 2012). Further research should evaluate the celeration values produced by autistic students.

Limitations

This study was conducted with four participants, so the results are not representative of the general population. Also, this study was conducted using a 1:1 teacher-to-student ratio and with a specific mathematical skill. More research is warranted with a different ratio and across different skills. In addition, following the guidelines from Fabrizio and Moors (2003), we defined application as the ability to generalise performance to novel situations. However, application has also been defined as the use of mastered skills when performing complex skills (Stocker et al., 2019). We did not assess the latter. Most importantly, the effect sizes used produced different results (which is understandable considering they are calculated differently), as in some cases there were ascending baseline trends. As a result, the magnitude of the effect of the intervention was unclear despite its positive outcomes.

Future directions

This study indicated a relationship between See-Say and See-Write. It would be beneficial to evaluate the relation between other sets. It would also be worth examining how other combinations of learning channels could affect students' performance and learning (for example, See.Hear-Write.Say). Also, more research is warranted on the ESAG-M test and its relation to performance criteria. Finally, future research could incorporate celeration values as part of decision rules to guide when participants exit baseline conditions to further improve internal validity.

Implications

The application of a Precision Teaching framework leads to beneficial educational outcomes for autistic students. The See-Say and See-Write learning channel sets are interdependent but to a certain extent. Therefore, practice should be delivered across all relevant sets. What is more, the See-Say set produces better generalisation than the See-Write, while the sequence of practice affects performance on each set. Finally, the overall performance was stronger on the See-Write set than the See-Say.

Data Availability

Supplementary materials, including the Standard Celeration Charts from this study, can be accessed at the FigShare data repository following this link: https://doi.org/10.6084/m9.figshare.c.4849509.v1.

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