Entering Aladdin's cave: developing an app for children with Down Syndrome

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Entering Aladdin's cave: Developing an app for children with Down syndrome

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Abstract

Tablets have much to offer children with learning difficulties, but evidence of their effectiveness to teach academic skills is limited and cannot be easily separated from the quality of the software. This paper analyses data from 3 iterative cycles of designing an app for children with Down syndrome to support their awareness of quantity through an inclusive game. Research with neurotypical children suggests that representation of quantity (or magnitude) is an area with considerable potential in supporting the foundations for children's mathematical learning. It has received little attention as an aspect for intervention for children with Down syndrome. Data collected in this study illustrate the need to carefully align the game mechanic to the target skills, strengthen levels of access, and introduce gradations of attentional demand. They also signal the interrelationship between children's cognitive and affective responses to the game, making it essential to find the optimal level of challenge. Children's strategies in response to mistakes indicate the importance of creating an agile responsive system. The data also suggest that developers routinely extend the number of features that are optional, enabling a greater level of personalization and a more inclusive game.

KEYWORDS

app design, Down syndrome, magnitude representation, mathematics, tablet

1 | INTRODUCTION

The introduction of the tablet has extended the reach of digital technologies to children with the most significant learning difficulties, providing them with a "cool" tool for learning (Culén & Gasparini, 2012). It has removed the challenges children experience in using the keyboard or mouse (Feng, Lazar, Kumin, & Ozok, 2010); the touch screen requires less cognitive processing and a simple motor response of pointing, all of which contributes to making tablets particularly suitable for user groups with intellectual disabilities (Kumin, Lazar, Feng, Wentz, & Ekedebe, 2016). Their portability provides real potential for self-instruction and independent learning across a range of contexts (Ayres, Mechling, & Sansosti, 2013). There is however some evidence to suggest that their very attractiveness can serve as a distraction (McEwen & Dube, 2015) as children enter an Aladdin's cave where the ease of touch-sensitive interfaces gives quick access to responsive sensory stimuli.

The affordances of technology can be significantly reduced by the quality of the software. Parents of children with Down syndrome (DS) report the difficulty of finding age-appropriate content as early skill programs are "naïve and boring," and easily outgrown (Feng et al., 2010). Stephenson and Limbrick (2015) in a review of studies that employ touch screen mobile devices with participants with developmental disabilities conclude that there is a paucity of robust evidence of effectiveness, especially with respect to their use to teach academic skills. They further conclude that the devices provide an easily accessible tool but that different apps will "present different challenges" (p. 3789) although they do not identify what they are. This paper explores those challenges as they arose in the development of an app specifically designed to support numerical awareness through an inclusive game, one that children with DS could access and play independently.

Children with DS experience particular challenges in mathematics often lacking the basic foundations on which to build (Abdelhameed, 2007; Faragher, Brady, Clarke, & Gervasoni, 2008). Although one might anticipate that they would experience difficulties due to an intellectual disability (typically scoring between 30 and 70 on IQ tests; Chapman & Hesketh, 2000), a combination of more specific difficulties can result in inconsistent and shaky counting skills with a consequent impact on numerical understanding (Nye, Fluck, & Buckley, 2001; Porter, 1999). For example, poor auditory sequential memory can make learning the string of count words quite problematic (Abdelhameed & Porter, 2011). Researchers have argued that too much emphasis is placed on counting rather than strengthening earlier visually based systems to provide a more robust foundation (Clarke & Faragher, 2014).

There is a strong case for the place of games in mathematics education. Games can produce high levels of motivation, and children benefit from well-defined rules and clear goals (Denham, 2015). A fun environment can offset the tedium of repeated practice that can be characteristic of teaching children with DS (Moni & Jobling, 2014). Games also have the potential for reducing anxiety, an important benefit given the evidence that highly anxious individuals represent quantity less precisely (Maloney, Erin, Ansari, & Fugelsang, 2011). Reviews however report the mixed effectiveness of online math games in the general population (Zhang, 2015) with evidence that a fun environment does not necessarily lead to the level of cognitive engagement required for learning (Iten & Petko, 2016). What may be more decisive is the instruction and support provided through the game. Denham (2015) identifies a number of important features of more successful mathematics games: learning targets well aligned with the game's objectives and placed in an interesting context; the right level of challenge and difficulty alongside scaffolding that promotes reflection; timely feedback; and the game mechanic (the system of rules for interacting with the game) consistent with the instructional objective. These overlap with the key elements that Hirsh-Pasek et al. (2015) identify for children at a young developmental age. These include active involvement and "mind on" engagement rather than mindless tapping and swiping, so that children attend with contingent interaction rather than get distracted by other stimuli such as sound effects or animation. Children are supported where there is a clear learning goal, often through social interaction with an on-screen character.

For this study, there are additional aspects to consider in designing an app: understanding the nature of progression within the learning target; addressing specific needs of our target group; and drawing on research on effective mathematics teaching.

1.1 | The learning target

Our learning target was derived from evidence concerning the earliest foundations of mathematics. Research with neurotypical children reveals that during the first 5 years (and beyond), children are able to make finer and finer discriminations between quantities that differ in the ratio of one to another. Children at 6 months, for example, are able to distinguish between arrays that differ in the ratio of 1:2; ratios of 2:3 at 9 months; 3:4 at 3 years; and 5:6 at 6 years (Brannon, Abbott, & Lutz, 2004; Halberda & Feigenson, 2008). Children with DS on the other hand appear to struggle in discriminating between quantities that vary by a ratio of 2:3 (Camos, 2009; Paterson, 2001; Paterson, Girelli, Butterworth, & Karmiloff-Smith, 2006), and this may explain some of their difficulty with mathematical skills. Research with typically developing children suggests that these early visual skills of magnitude representation provide a foundation for later mathematical learning (Gilmore, McCarthy, & Spelke, 2010; Libertus, Feigenson, & Halberda, 2011). Our aim therefore was to develop an app that would strengthen these skills through a game mechanic that required the discrimination of quantities where the level of difficulty was determined by ratio rather than absolute number.

1.2 | Learning and children with Down syndrome

Although research does not provide good evidence to suggest a distinct pedagogic approach for children with DS (Wishart, 2005), there are a number of potential areas of difficulty that impact on their learning. Of particular relevance here, are aspects of attentional control. For example, Borella, Carretti, and Lanfranchi (2013) illustrate their difficulty in controlling attention to irrelevant and distracting information and suppressing responses to it. J. G. Wishart and Duffy (1990) report fluctuating levels of engagement across a range of tasks and how this impedes both acquisition of new skills and understanding and the consolidation of previous learning. Children's disengagement occurs in the face of success as well as failure (Faragher et al., 2008), suggesting that issues of motivation need to be considered alongside task difficulty.

Children with DS are more likely than their peers to experience auditory impairment (Park et al., 2012), and the incidence of visual impairments is also higher with refractive errors increasing in childhood and near vision more likely to be consistently out of focus (Cregg et al., 2001). Both impact on the clarity of information to be processed. Visual processing appears to be stronger than auditory processing (Baddeley & Jarrold, 2007) although this does not hold true for every context; in part, it depends on the type of presentation (whether sequential or simultaneous) and the kind of visual spatial task that is presented (Yang, Conners, & Merril, 2014). There is some evidence that these learners do better at discrimination tasks when the information is located in a particular part of the screen rather than dispersed across the screen (Belacchi et al., 2014). Of relevance to their interaction with technology, children often experience a number of difficulties in making precise fine motor movements (Fidler & Rogers, 2006).

These characteristics have a number of design implications. There are important advantages to presenting material visually, but it must have a visually clear display, where the important elements are distinctive and easy to locate. It should not be reliant on auditory cues or require delicate motor responses. If it is to be accessible to all children with DS, it requires careful attention to the levels of difficulty and to the type of feedback and reward.

1.3 | Math intervention and children with Down syndrome

Browder, Spooner, Ahlgrim-Delzell, Wakeman, and Harris (2008) in a comprehensive review of mathematics instruction with children with severe and moderate intellectual disabilities reveal that two properties are characteristics of successful interventions; a systematic approach and "in vivo" learning. The majority of intervention studies target two areas: numbers and operations (adding and subtracting) and money. None target the area of magnitude representation. Lemons, Powell, King, and Davidson (2015), in a more recent review of the efficacy of math intervention programs focusing specifically on children with DS, found nine papers with a robust methodology that report learning outcomes. Only one paper provides clear evidence using computer-assisted learning. Features of the other eight nondigital studies that met their inclusion criteria include direct instruction and modelling of responses, fading the support given, and using praise. The single paper using computer-assisted learning that met their criteria compared the use of a multimedia software program with traditional paper and pencil methods to teach counting and cardinality (Ortega-Tudela & Gómez-Arizaw, 2006). It was a relatively small study with 10 children with DS in an experimental group and 8 in the control, but significant differences in favour of the multimedia group were found across all aspects of counting and cardinality. The authors argue that in part the nature of the feedback given reinforced children's understanding of the task. More recently, Agheana and Duta (2015) used a commercially available preschool app to successfully teach how to count, add, and subtract. Eight children with DS outperformed a matched group who received practice with concrete materials. The authors emphasize the possibilities of multimedia materials that utilize “dynamic and appealing” presentations (p. 45).

1.4 | Evaluation of the app

The lack of robust studies may well reflect the problematic nature of evaluating an iPad game alongside its development. Typically, evaluations focus on outcomes—indeed much of the literature is reviewed with respect to whether specific learning outcomes are reported and then whether the methodology or research design has been sufficiently robust to draw conclusions that those outcomes were a result of that intervention. Stephenson and Limbrick (2015) in reviewing evidence on the use of tablets with people with developmental disabilities identified 251 refereed outputs of which 36 met their screening criteria. They do not report on qualitative data. Qualitative data provide the opportunity to understand the process of learning and how particular outcomes are reached and for designers to learn from it. Evidence of the way that children interact both with the tablet and with the game is particularly important in guiding new developments (Marcedo, Trevisan, Vasconcelos, & Clua, 2015), especially where it is placed alongside theories of how children learn and in this particular case an understanding of the challenges they may face. Focusing only on quantitative data may effectively screen out valuable insights, ones that guide and shape refinements. A flexible design can also offset the limitations of small-scale studies through taking each iteration to new groups.

Given the wide range in ability of children with DS, some standard comparator is required to identify differences between groups. Although studies often use non-verbal IQ or mental age measures, this is usually because the authors wish to compare the ability of children with DS with that of typically developing children. That was not the purpose here as we were interested in how children interacted with the game. In this study, we used children's performance on a nondigital game, one that also incorporated the choice of different quantities. In mathematics, changes in context can effectively change the nature of the activity, as children may utilize everyday understandings and procedures in one context but not in another (Lave, Murtaugh, & de la Rocha, 1984). Performance on a nondigital task serves to raise interesting questions about these contextual differences. Whereas the digital game was subject to changes and developments, the parallel game was a fixed entity throughout the period.

The following questions guided this study: Are children with DS engaged by the game? Are they able to discriminate arrays of 2:3 using a tablet game? Is their profile of attainment better or worse than with a parallel card game? How do they interact with features of the game? The project was research council funded as a rapid research and development activity, and therefore, there was no scope for evaluating the app in relation to progress in mathematics. However, addressing these questions was an important starting point for understanding the potential of the game.

2 | METHODOLOGY

The study included three iterative design cycles with the collection of qualitative and quantitative data.

2.1 | Participants

The study included children aged 3.5–19 years with more boys than girls, reflecting the higher incidence of DS in males (Bishop, Huether, Torfs, Lorey, & Deddens, 1997). Children in the first two cycles were recruited through a DS organization and mainly attended mainstream schools. In the final cycle, we approached two special schools in another region to avoid a skewed sample. Table 1 sets out the details of our participants.

Ethical procedures followed the university guidelines with formal approval granted. Written consent was sought individually from parents and verbally from children. We described the purpose of our research activity in simple terms to children—that they were helping us in the development of a new game—and invited them to take part. They were seen individually in a quiet room accompanied by a parent or teaching assistant, or in a few instances, due to their own preferences, they took part in the activity alone. We were mindful of the need for an “ethical radar” (Skanfors, 2009), responding immediately to non-verbal signs that they wished to discontinue the activity.

2.2 | Procedures

Children in all three cycles received two tasks that were counterbalanced in order between children.

iPad game: The consistent feature of the game involved Millie, “an intrepid space explorer” whose path across the planets is strewn with obstacles and who requires the player's help. The central game mechanic hinges on the player being able to look at two groups of dots and correctly choose which group has more dots so that her path is made smooth. A demonstration and practice trial was given prior to their independent play.

TABLE 1 Participants

	Number of children	Age range years and months (average)	Boys	Girls
Iteration 1	16	3.5–16.10 (9.4)	11	5
Iteration 2	12	3.6–9.11 (7.1)	7	5
Iteration 3	36	5.8–19.0 (13.0)	21	15

Responses of correct or incorrect choice were recorded. Observational field notes were kept of the child's level of interest in the game and their engagement with different features as they were introduced.

Card game: A series of card pairs were presented; on each was depicted a random array of dots. Each pair of cards utilized dots of the same colour and format, differing only in quantity. A large and a small set size were presented of each of the following ratios: 1:3 (1:3, 3:9); 1:2 (1:2, 4:8); 2:3 (2:3, 4:6); 3:4 (3:4, 6:8); 5:6 (5:6, 10:12); and 10:11. The child was invited to pick the card "which has more" and to turn it over to see if it had a star on the back, indicating that they were correct. Children were given a demonstration and practice trial prior to completing the set. Small and large sets were alternated. Responses were recorded of the correct or incorrect choice of "more."

Data analysis: Quantitative data of children's correct responses in relation to ratio and set size were analysed using SPSS to provide descriptive statistics and boxplots and explore skewedness and kurtosis, which indicated the need for nonparametric statistics. Wilcoxon signed-rank tests were used to compare differences between children's performance on the iPad and with the cards.

Iteration 1. Planet Water World was presented without sound or music. The motivation of the game largely lay with the desire to see Millie move and reach the flagpole where she danced. As Millie walked along the path, she encountered crevasses, at this point, the player had to choose and tap on one of two square arrays with dots positioned much as they would be on a dice varying in the ratio of 1:2 (1:2; 2:4; 3:6; 4:8; 5:10) and the ratio of 2:3 (2:3; 4:6; 6:9). The selection of "more" made bricks move into place to allow her to walk along the surface. Arrays were randomly generated so that no two children experienced exactly the same game. Our aim with the first iteration was to see how children engaged with the game and whether they were able to choose between the two arrays with the set size of 1:2 and 2:3.

The data in Table 2 and Figure 1 reveal the range of responses, with performance on our target ratio of 2:3 being above chance (mean 68.9%; median 69%) and surprisingly slightly higher than ratio 1:2.

The boxplot shows the higher degree of dispersion and lower median scores of pupils' discriminations of ratio 1:2 (Mdn 58) compared with 2:3 (Mdn 69) but with no statistically significant difference between the two (N = 16, T = 103, p = .07, z = 1.8).

Ten children also played the card game that gave some indication of the extent to which their responses varied with the format.

As Table 3 reveals, this subgroup represented the range of responses on the iPad game. As with the larger group, they did very slightly better on the harder 2:3 discriminations with average responses above the level of chance. Their performance with the card game however showed, in accordance with the literature, greater difficulty with discriminations that varied in the ratio of 2:3. Two children performed better on the iPad game, and eight performed better with the cards, but there was no significant difference at a group level between their performance on the iPad and the card game for ratio 1:2 (T = 33, p + .56, z = 0.58) or for ratio 2:3 (T = 16.5, p = .48, z = −0.7).

TABLE 2 Percentage of correct responses in the first iteration of the game

	N	Minimum score (%)	Maximum score (%)	Mean (%)	Standard deviation
Ratio 1:2	16	33	100	59.7	19.5
Ratio 2:3	16	44	100	68.9	16.3

Our observational field notes revealed that some parents and children perceived the game to require counting skills. For example, two parents spontaneously said when their child got correct responses that it was "pot luck" (they couldn't count that many) and that they were guessing. One child tried counting the dots to make her selection. Counting transformed the activity to one of absolute rather than relative number and therefore a harder and more advanced task. This had important implications for the format of the mechanic that, because of its structured appearance and likeness to a dice, unintentionally reinforced the message that this was a game around counting.

The children displayed rapid repeated tapping, their desire to make something happen outstripping their recognition of the rules of the game. The home button proved particularly attractive, its iconic features drawing their attention. Pressing this button led back to the beginning of the game, delaying the reward of Millie dancing. Thus, children were effectively distracted from the task. Some children found it tricky to look at both the mechanic and Millie and focused on one element to the exclusion of the other. This militated against recognizing the impact of their response. This was particularly problematic for those children who wore glasses whose field of vision was lessened. Some parents suggested that their child would find it more engaging if there was sound.

Iteration 2. The challenge for the developers lay with changing the tapping to "minds on" engagement with the game. In the second version, Millie's feedback, shaking her head when the wrong button was selected, was accompanied by a sound, with the option for music throughout the game. The die were replaced by distinctive round buttons with spots randomly arranged in ratios of 1:2 and 2:3 (see Figure 2), comparable with those in the research literature.

Data from 12 children who tested this version is set out in Table 4 and Figure 3. Children in this second iteration were slightly younger than the first, but the same broad range of responses were seen, varying from incorrect to near perfect scores. Their average performance was around the level of chance with the easier ratio of 1:2, slightly higher for 2:3 but, as shown in the boxplot, with little difference between the medians. A Wilcoxon signed-rank test revealed that there was no statistically significant difference between performance on 1:2 ratio (median 53) than 2:3 (median 56), N = 11, T = 41, p = .45, z = 0.71.

A subsection also played the card game, and their responses are listed in Table 5. In both contexts, they did better with the 2:3 ratio, their higher group average performances being with the cards but with no significant difference between performance on the iPad and the card game for ratio 1:2 (T = 29.5, p = .4, z = 0.83) or ratio 2:3 (T = 21, p = .67, z = 0.42).

Individual data for the nine children revealed that all four girls and one boy performed better on the card game than with the iPad for both ratios, three boys performed better on the iPad than the cards, and one boy showed a mixed profile.

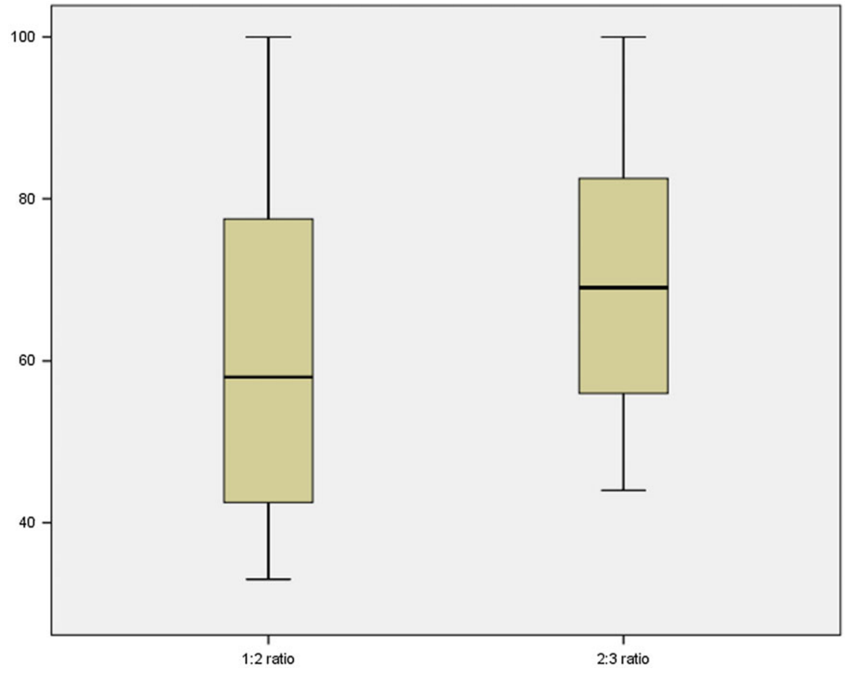

FIGURE 1 Boxplot of children's percentage scores of ratios 1:2 and 2:3 (first iteration) [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Performance of children that did both digital and card game (first iteration)

	Discriminations of ratio 1:2		Discriminations of ratio 2:3	
N = 10	Digital	Cards	Digital	Cards
Range of successful responses (%)	40–100	0–100	44–100	0–100
Average percentage of successful responses (%)	66	73	70	57
Median performance	65	83.5	67.5	50

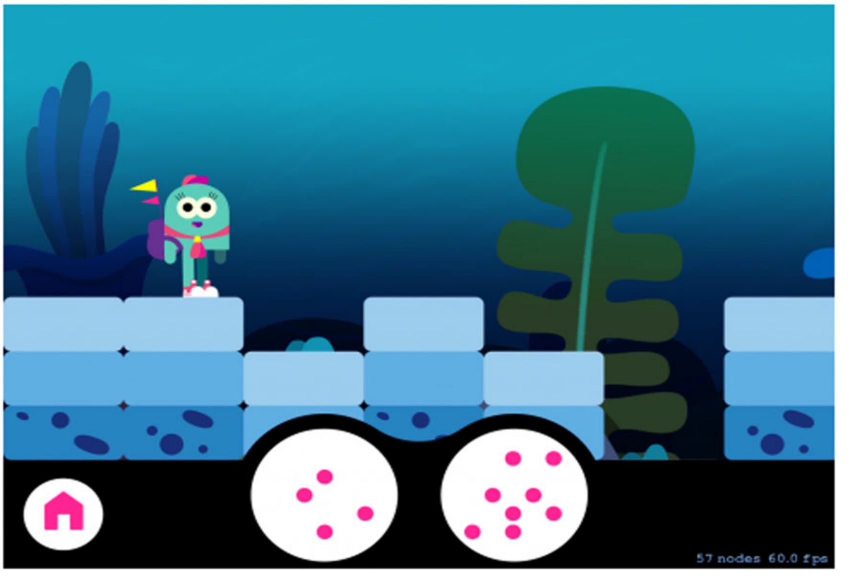

FIGURE 2 App design second iteration: Water World [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 4 Percentage of correct responses in the second iteration of the game

	N	Minimum score (%)	Maximum score (%)	Mean (%)	Standard deviation
Ratio 1:2	12	29	92	51.8	19.4
Ratio 2:3	12	30	100	60.2	24.1

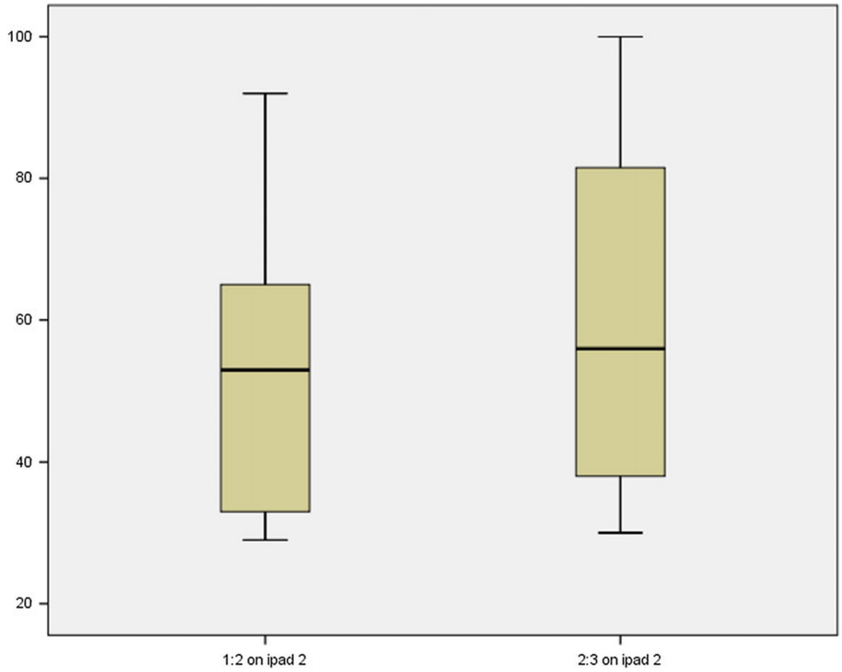

FIGURE 3 Boxplot of children's percentage scores of ratios 1:2 and 2:3 (second iteration) [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 5 Performance of children that did both the cards and iPad game (second iteration)

	Discriminations of ratio 1:2		Discriminations of ratio 2:3	
N = 9	2nd iPad	Cards	2nd iPad	Cards
Range of successful responses (%)	33–92	0–100	30–100	0–100
Average percentage of successful responses (%)	54	64	67	71
Median (%)	56	67	67	67

Our observational field notes suggest that a number of children appeared to be disadvantaged by the iPad game. Children continued to make repeated and frequent taps, and although these were more precisely located on the buttons, it could not be described as "minds on" activity. The change in appearance had brought the game mechanic closer to the learning goal but possibly made the game less accessible, although comparison between the children's responses in Cycles 1 and 2 is not straightforward given small group sizes, large age, and ability range, all of which preclude against hard and fast judgements. The focus of the next iteration therefore lay with the provision of supports as well as progression within the game, so that children at the earliest levels experienced shorter and easy games where they would learn the rules, and for those who already understood these, there would be further levels of difficulty.

Iteration 3. The entry level in the next iteration of the game was made easier to build confidence in accessing the game. A support button was offered, which, if pressed, made the correct answer glow. An arrow and "more" also appeared on the screen. Finally, a dynamic difficulty adjustment (DDA) system was added, which adjusted the difficulty of the challenge as the player progressed to the next planet. A new "Native World" was added based around quantities in the ratio 2:3, but if the player made repeated mistakes, an easier ratio of 1:3 was presented. This had many advantages but made it difficult to compare one player with another when they advanced to the second planet as, depending on their accuracy, they were engaged in slightly different games. For games with a score of 80% or more, the player won a "collectible," an item that Millie had discovered on the planet. These appeared in a new screen where they could be dragged and dropped into a rucksack. Three further planets were added, two involved the selection of less (see Figure 4) and one involved both more and less, thereby extending the level of challenge to a wider range of children.

In total, 36 children aged 5–19 years, 21 boys and 15 girls, tested the third iteration. Of these, 30 also did the card game. Children started with Water World (ratio 1:4) before going on to Native World (ratio 2:3). If they encountered difficulty, the ratio between the quantities changed to 1:3 gradually returning to 2:3 when they were successful.

Table 6 sets out the responses of this larger group. Average scores for both planets were high: 95% for players of Water World (ratio 1:4) and 85% for Native World (with ratios of 2:3 and 1:3). In contrast to the previous iterations, the boxplot in Figure 5 shows a skewing with median scores above 80% but with a long tail to the data for Native World and six outliers (see below) for Water World. There was a significant difference between pupils' scores on the two planets (N = 29, T = 21.5, z = −3.27, p = .001, effect size 0.43) with children's scores on the easier ratio 1:4 higher.

The change in ratios of the third iteration of the iPad game makes performance on the card game no longer directly comparable, but it is

FIGURE 4 Native World with additional instructional support (third iteration) [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 6 Percentages of correct performance on the third iteration of the game

	N	Minimum score (%)	Maximum score (%)	Mean (%)	Standard deviation	Median (%)
Water World (ratio 1:4)	30	60	100	95	9.6	100
Native World (ratio 1:3/2:3)	29	52	100	85	13.8	85

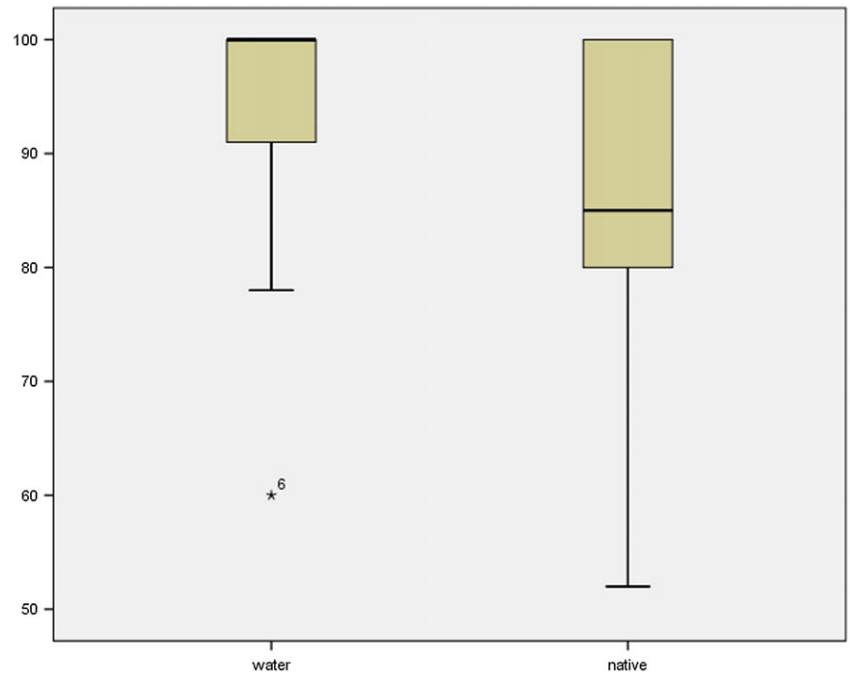

FIGURE 5 Boxplot of children's percentage scores on Water (ratio 1:4) and Native (ratio 1:3–2:3) Worlds (third iteration) [Colour figure can be viewed at wileyonlinelibrary.com]

useful for indicating that the group, while spanning the usual range of ability, revealed higher mean scores than previous groups, with many scoring at ceiling level for both ratios (see Table 7).

This third version proved to be accessible for most players, with four exceptions. Three children had behavioural support needs that impeded their independent playing of the game. One, for example, required the assistant to tap the quantity and only intermittently did so himself. The fourth player had a significant visual impairment, so the display with fewer dots was more easily seen and therefore more salient. Additionally, due to technical

TABLE 7 Children's performance on the card game

	N	Minimum score (%)	Maximum score (%)	Mean (%)	Standard deviation	Median (%)
Card ratio 1:2	30	0	100	80.4	31.8	100
Card ratio 2:3	30	0	100	75.9	33.8	100

problems, we did not record the specific responses of two children. Notably, however, on Water World, 26 of the 30 children had at least one game where they scored 80% or more, providing a clear indication that they both understood the game and were able to do it.

The new planet, Native World, with its smaller ratios proved more challenging. The games were longer as Millie's walk to the end pole involved more crevasses, and these were often deeper, requiring repeated "more" choices as brick by brick the path was restored. Only eight of the group managed to score the full 100% on one or more games. However, 23 children had scores above 80% and therefore received collectibles in reward for a high score. A few children went on to try other planets; seven tried Forest World, which required a choice of "less" for arrays of 2:3. This shift to choosing the opposite proved tricky, but three succeeded scoring 70–100%, and one young man tried the next planet, which required responses of both "more" or "less" depending on whether Millie was faced with a crevasse or a tower of bricks, a very challenging game requiring close attention, and he scored 86%.

There were some interesting patterns of responding on this iteration, revealing different player profiles. The motivation for some was clear, to get a high score and to receive a collectible. Often they played more slowly and carefully. A few gave self-prompts signing "more" before the selection. Typically, these players did well. In contrast, the sound of a mistake was hugely amusing for some children, and we could not be sure whether it provided an alternative goal to a correct selection. Conversely, nine players did not like making errors or the noise and became reluctant to continue. These players often shifted from using a magnitude to a locational cue, selecting the other side on their next turn as if burnt by the previous selection. If this was also a mistake, they shifted sides again. Thus, errors often led to a string of wrong answers and the player withdrawing from the game. Unusually, one player returned to the Water Planet when he started making mistakes on Native World and returned to play the harder game when he got 100% right, confidence restored.

The inclusion of the "collectibles" and a short simple version of the game gave experience for those whose understanding was less well established. The activity of putting the collectibles in the rucksack meant that more or less time was spent on the harder quantity choice elements.

3 | DISCUSSION

The aim of the app was to support the ability of children with DS to discriminate differences in quantity, through the development of an inclusive game. We asked: Are children able to discriminate 2:3 using a tablet game? Is their profile of attainment better or worse than a parallel card game? The data for answering these question are limited to the first two iterations of the game. There was wide variation in children's accuracy in discriminating ratios of 2:3 and no statistical difference to the easier ratio of 1:2. Individual-level data suggested that *overall*, children in these first two iterations were slightly more likely to respond better with the cards with fewer children performing better with the iPad. A number of factors contributed to this, including the visual clarity of the app along with the salience of particular icons.

The wide variation within the group led to the introduction of an easier entry-level game of ratio 1:4 (as well as harder extensions) and a DDA. The group average rose to 94% on the easiest ratio 1:4 and 85% on the 1:3/2:3 ratio, with a significant difference in their performance between the two. Just under a quarter went on to explore further planets testing their skills of selecting less and then "more or less." In many ways, these children exceeded expectations, not only in discriminating between arrays that varied in the ratio of 2:3 but also in applying this skill flexibly to conditions that required choices or both more and less. Performance on the card game suggested that this older special school group were, on average, better at discriminating than the previous two groups but with greater individual variation.

We also asked: Are children engaged by the game? In total, five boys proved reluctant to engage with the game, and one other watched others play until he overcame his hesitancy and asked to have a turn. Three displayed a challenging behaviour, and for one, this seemed a response to the research situation, and was taken as a sign of dissent. The fifth boy had a significant visual impairment and "less" proved more visible than "more."

Engagement proved a mixed blessing. The literature has revealed how children are attracted to explore outside the task with an iPad (Sheppard, 2011) and diverted from the expected range of responses (Culén & Gasparini, 2012). Children in this study explored the other attractions of the iPad. In particular, they were drawn to the home button that served to distract their game play and led to a distancing of the final reward as pressing it led to the start of a new game. Other elements of the display also proved engaging, children trying the tactic of dragging objects on the screen as well as tapping to elicit changes. Thus while the novelty of the game engaged their attention at the same time elements of this served to distract them from the goal. Recognizing that swiping and tapping were engaging activities, we found a place for them in the reward of collectibles that could be positioned in a rucksack. With this addition, the game had a hierarchy of different rewards, each providing a different kind of incentive: a dance from Millie, a score, and the collection of objects. This variety improved the accessibility of the game.

Feedback and reinforcement play an important role in the acquisition process for children with DS (Lemons et al., 2015), and these aspects were progressively introduced across the cycles. The reinforcement expanded from rewarding engagement to accurate responding. Some feedback proved a perverse incentive. When Millie shook her head for an incorrect response, a sound was made. For some, this concentrated their mind on making considered responses, aiding attention to the game. For others, it provided a disincentive, because either it became a desired reward (Feng et al., 2010) or conversely it served as a punishment for children who disliked making mistakes. In hindsight, this sound could have been made as an optional feature, in the same way as the music. Other researchers have observed disengagement on encountering failure (Wishart, 2001), making issues of progression particularly important. This serves to remind the app designer of the importance of careful planning of levels of difficulty if a game is to be accessible to all children.

Research has indicted the importance of structured approaches with children supported through small steps towards increasing complexity or difficulty (Browder et al., 2008; Lemons et al., 2015). Informed by developmental research, this was conceived at the outset in relation to the size of the ratio between the arrays, and by the third iteration, the starting point had shifted from 1:2 to 1:4 to enable children at the earliest stages to access the task. Progression also took the form of increasing cognitive effort as within each planet Millie's path became longer, moving from a small number of obstacles that could be overcome by a single choice to a longer path where the depth of the crevasse required repeated choices as each brick was replaced in turn. In the entry-level game, the flagpole denoting the end of the game was quickly in sight; for higher levels, it was not. Thus, the task required increasing levels of sustained attention and perseverance with greater levels of effort required for each game.

The introduction of the DDA produced an additional layer of differentiation, tailoring the game through altering the ratio based on children's error responses. We became aware that location was also a determining response factor, with some children favouring one side rather than another. With a larger sample in the third iteration, it was possible to place this in the context of children's response to failure, as they shifted strategy in the course of playing the games: from discrimination of quantity to the position of the array. This illustrates well the interaction between affective engagement and finding the optimal level of challenge. Although the DDA changed the ratio to an easier form, it was not necessarily sufficient to direct the child away from locational responding. A more complex system of individualization was needed, one that recognized that children at the same stage of acquisition have reached it with a different pattern of responding, at different speeds and requiring different pathways of support.

One of the challenges encountered was to provide support in a manner that does not interrupt the game (Ter Vrugte et al., 2015). Few children independently used the support button that introduced the word "more" on the screen and an arrow. Both were reminiscent of a lesson, making this an overtly instructional device and potentially detracting from the fun. This online support proved less effective than the presence of a second player. During our third iteration, Lenny (age 5) was joined by his younger sister who was keen to try the game. He played on his own and struggled to consistently choose "more," before they then took it in turns to make a choice. In a very short time, Lenny was getting all his choices correct, the experience of watching his sister learn benefitting him. We also found we could support children who were wary of trying the game by asking them to help others (usually the TA), which gave them confidence to play. It was not therefore necessary to always conceive of the "other" as being the more capable partner but one that enables the player to reconfigure their role and offset the experience of failure, giving the activity a new meaning. This opportunity for "tutoring" others could be built into future iterations of the game.

3.1 | Limitations and future directions

One of the challenges of planning research around the design process is of not knowing what the outcome of the design will be. The unforeseen developments here meant that our standard comparator, the card game, was no longer completely fit for purpose, as it employed different ratios to the final version of the game. However, the card game did provide a stable indication of the differences between the groups in relation to their discrimination between ratios. This indicated that the children we included had a broad range of skills and suggested that our recruitment practices of including children from both special and mainstream education had been effective.

There was a trade-off in the development process. The study had enabled us to achieve breadth with a wide range of children participating in the research process, allowing us to test issues of access across children with a variety of additional needs across three iterations of fine tuning the game; their levels of engagement indicated its potential for cognitive learning, but we did not formally evaluate whether children acquired new skills over time. We now need to examine whether their engagement survives the test of time when aspects of the game were no longer novel, whether it results in stable new learning. This forms the next step, drawing on the data here to identify children with different profiles of learning using a fixed rather than flexible research design with pretest and posttest measures and investigating how these skills were then generalized to different settings.

Working collaboratively across a team engaged in a range of activities produced some tensions and dilemmas. There were many benefits to bringing together the craft of game design with the researcher's experience of early mathematical skills, but this also brought competing agendas for creativity and exploration within the design team versus the research evidence base of the importance of structure and goal-directed small steps. Unforeseen alterations to ratios arose during the design process that had consequences for the research, and some aspects rose more intuitively from the data with limited opportunity for testing out. For example, more specific data could be collected on children's responses to failure thereby informing the programming of the DDA.

4 | CONCLUSIONS

Research with neurotypical children and those with specific mathematical difficulties suggest that magnitude representation is an area with considerable potential in supporting the foundations for children's learning. This has been an area of neglect for children with DS until now. Despite the growth in tablet use, there is limited research to guide the development of an app for children with DS. The iterative process of design and testing described here reveals the challenges of creating a bespoke program that meets the needs of a range of learners. In summary, this research highlighted the importance of considering the following:

- the salience of some icons together with clarity of the visual display;
- the multilayered nature of progression;
- the interaction between affective engagement and level of challenge;
- attending to different patterns and strategies of responding; and
- deployment of a dynamic difficulty adjuster that is responsive to these differing patterns.

A number of features could be made optional, enabling a degree of personalization that goes beyond that usually provided with respect to sensory aspects, text, and physical manipulation (Hersch, 2016). Here, the feedback elements have been highlighted together with the type and availability of support provided through a "help" button.

This research has demonstrated that with adjustments to the design, learners can be actively engaged to the point of exceeding expectations in an area in which previous research has indicated difficulty (Paterson, 2001; Paterson et al., 2006). This research also adds to our understanding of the situations in which children with DS disengage with learning. It illustrates how mistakes can lead to the adoption of inadequate strategies and the perseveration of failure. The design and responsiveness of an app is therefore particularly significant in providing the appropriate levels of challenge. This in turn indicates the importance of investing time in iterative cycles of development, highlighting the place of qualitative observational data in the design process.

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Ethical approval was received from the universities of Bath and Reading.

CONFLICT OF INTEREST

The author declares no conflict of interest.

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REFERENCES

Abdelhameed, H. (2007). Do children with Down syndrome have difficulty in counting and why? *International Journal of Special Education*, *22*(2), 129–139.

Abdelhameed, H., & Porter, J. (2011). Verbal short-term memory performance in pupils with Down syndrome. *International Journal of Disability, Development & Education*, *57*(4), 427–438.

Agheana, V., & Duta, N. (2015). Achievements of numeracy abilities to children with Down syndrome: Psycho-pedagogical implications. *Procedia-Social and Behavioural Sciences*, *186*, 38–45.

Ayres, K. M., Mechling, L., & Sansosti, F. J. (2013). The use of mobile technologies to assist with life skills/independence of students with moderate/severe intellectual disability and/or autism spectrum disorders: Considerations for the future of school psychology. *Psychology in the Schools*, *50*, 259–271. https://doi.org/10.1002/pits.21673

Baddeley, A., & Jarrold, C. (2007). Working memory and Down syndrome. *Journal of Intellectual Disability Research*, *51*(12), 925–931.

Belacchi, C., Passolunghi, M. C., Brentan, E., Dante, A., Persi, L., & Cornoldi, C. (2014). Approximate additions and working memory in individuals with Down syndrome. *Research in Developmental Disabilities*, *35*(5), 1027–1035.

Bishop, J., Huether, C. A., Torfs, C., Lorey, F., & Deddens, J. (1997). Epidemiologic study of Down syndrome in a racially diverse Californian population. 1989–1991. *American Journal of Epidemiology*, *145*(2), 134–147.

Borella, E., Carretti, B., & Lanfranchi, S. (2013). Research in inhibitory mechanisms in Down syndrome: Is there a specific or general deficit? *Research in Developmental Disabilities*, *34*, 65–71.

Brannon, E. M., Abbott, S., & Lutz, D. J. (2004). Number bias for the discrimination of large visual sets in infancy. *Cognition*, *93*, B59–B68.

Browder, D. M., Spooner, F., Ahlgrim-Delzell, L., Wakeman, S. Y., & Harris, A. (2008). A meta-analysis for teaching mathematics to individuals with significant cognitive disabilities. *Exceptional Children*, *74*, 404–432.

Camos, V. (2009). Numerosity discrimination in children with Down syndrome. *Developmental Neuropsychology*, *34*(4), 435–447.

Chapman, R. S., & Hesketh, L. J. (2000). Behavioral phenotype of individuals with Down syndrome. *Mental Retardation and Developmental Disabilities Research Reviews*, *6*(2), 84–95.

Clarke, B., & Faragher, R. (2014). Developing early number concepts for children with Down syndrome. Chapter 6. In R. Faragher, & B. Clarke (Eds.), *Educating learners with Down syndrome*. London: Routledge.

Cregg, M., Woodhouse, J. M., Pakeman, V. H., Saunders, K. J., Gunter, H. L., Parker, M., … Sastry, P. (2001). Accommodation and refractive error in children with Down syndrome: Cross-sectional and longitudinal studies. *Investigative Ophthalmology & Visual Science*, *42*, 55–63.

Culén, A., & Gasparini, A. (2012). Tweens with the iPad classroom—Cool but not really helpful? In e-Learning and e-Technologies in Education (ICEEE), *2012 International Conference 1–6*

Denham, A. R. (2015). Supporting conceptual understanding of the associative and distributive properties through digital gameplay. *Journal of Computer Assisted Learning*, *31*, 706–721. https://doi.org/10.1111/jcal.12113

Faragher, R., Brady, J., Clarke, B., & Gervasoni, A. (2008). Children with Down syndrome learning mathematics: Can they do it? Yes they can. *Australian Primary Mathematics Classroom*, *13*(4), 10–15.

Feng, J., Lazar, J., Kumin, L., & Ozok, A. (2010). Computer usage by children with Down syndrome: Challenges and future research. *ACM Transaction on Accessible Computing*, *2*(3), 1–44. https://doi.org/10.1145/1714458.1714460

Fidler, S. H., & Rogers, S. (2006). Early learning and adaptive behavior in toddlers with Down syndrome: Evidence for an emerging behavioural phenotype? *Down Syndrome, Research and Practice*, *9*(3), 37–44.

Gilmore, C. K., McCarthy, S. E., & Spelke, E. S. (2010). Non-symbolic arithmetic abilities and mathematics achievement in the first year of formal schooling. *Cognition*, *115*(3), 394–406.

Halberda, J., & Feigenson, L. (2008). Developmental change in the acuity of the "number sense": The approximate number system in 3-, 4-, 5-, and 6-year-olds and adults. *Developmental Psychology*, *44*(5), 1457–1465.

Hersch, M. (2016). Classification framework for ICT-based learning technologies for disabled people. *British Journal of Educational Technology*, *48*, 768–788. https://doi.org/10.1111/bjet.12461

Hirsh-Pasek, K., Zosh, J. M., Golinkoff, R. M., Gray, J. H., Robb, M. B., & Kaufman, J. (2015). Putting education in "educational" apps: Lessons from the science of learning. *Psychological Science in the Public Interest*, *16*(1), 3–34.

Iten, N., & Petko, D. (2016). Learning with serious games: Is fun playing the game a predictor of learning success? *British Journal of Educational Technology*, *47*, 151–163. https://doi.org/10.1111/bjet.12226

Kumin, L., Lazar, J., Feng, J. H., Wentz, B., & Ekedebe, N. (2016). A usability evaluation of workplace-related tasks on a multi-touch tablet computer by adults with Down syndrome. *Journal of Usability Studies*, *11*, 2118–2142.

Lave, J., Murtaugh, M., & de la Rocha, O. (1984). The dialetic of arithmetic in grocery shopping. In B. Rogoff, & J. Lave (Eds.), *Everyday cognition: Its development in social contexts* (pp. 67–69). Cambridge: Harvard University Press.

Lemons, C. J., Powell, S. R., King, S. A., & Davidson, K. A. (2015). Mathematics interventions for children and adolescents with Down syndrome: A research synthesis. *Journal of Intellectual Disability Research*, *59*, 767–783. https://doi.org/10.1111/jir.12188

Libertus, M. E., Feigenson, L., & Halberda, J. (2011). Preschool acuity of the approximate number system correlates with school math ability. *Developmental Science*, *14*(6), 1292–1300. https://doi.org/10.1111/j.1467-7687.2011.01080

Maloney, Erin, A., Ansari, D., & Fugelsang, J. A. (2011). The effect of mathematics anxiety on the processing of numerical magnitude. *The Quartley Journal of Experimental Psychology*, *64*(1), 10–16.

Marcedo, I., Trevisan, D.G., Vasconcelos, C.N., & Clua E. (2015) Observed interaction in games for Down syndrome children *48th Hawaii International Conference on Systems Sciences*. IEEE https://doi.org/10.1109/HICSS.2015.86

McEwen, R., & Dubé, A. K. (2015). Engaging or Distracting: Children's Tablet Computer Use in Education. *Educational Technology & Society*, *18*(4), 9–23.

Moni, K. B., & Jobling, A. (2014). Challenging literate invisibility: Continuing literacy education for young adults and adults with Down syndrome. Chapter 10. In R. Faragher, & B. Clarke (Eds.), *Educating learners with Down syndrome*. London: Routledge.

Nye, J., Fluck, M., & Buckley, S. (2001). Counting and cardinal understanding in children with Down syndrome and typically developing children. *Down Syndrome, Research and Practice*, *7*, 68–78.

Ortega-Tudela, J. M., & Gómez-Arizaw, C. J. (2006). Computer-assisted teaching and mathematical learning in Down syndrome children. *Journal of Computer Assisted Learning*, *22*, 298–307.

Park, A. H., Matt, M. D., Wilson, A., Paul, M. D., Stevens, T., Harward, R., & Hohler, N. (2012). Identification of hearing loss in pediatric patients with Down syndrome. *Otolaryngology–Head and Neck Surgery*, *146*, 135–140.

Paterson, S. (2001). Language and number development in Down syndrome. *Down Syndrome, Research and Practice*, *7*(2), 77–86.

Paterson, S. J., Girelli, L., Butterworth, B., & Karmiloff-Smith, A. (2006). Are numerical impairments syndrome specific? Evidence from Williams syndrome and Down's syndrome. *Journal of Child Psychology and Psychiatry*, *47*(2), 190–204.

Porter, J. (1999). Learning to count: A difficult task? *Down Syndrome Research & Practice*, *6*(2), 85–94.

Sheppard, D. (2011). Reading with iPads - the difference makes a difference. *Education Today*, *3*, 12–15.

Skanfors, L. (2009). Ethics in child research: Children's agency and researchers' 'ethical radar'. *Childhoods Today*, *3*(1), 1–22.

Stephenson, J., & Limbrick, L. J. (2015). rgg. *Autism Dev Disord*, *45*, 3777–3791. https://doi.org/10.1007/s10803-013-1878-8

Ter Vrugte, J., de Jong, T., Wouters, P., Vandercruysse, S., Elen, J., & de Oostendorp, H. (2015). When a game supports prevocational math education but integrated reflection does not. *Journal of Computer Assisted Learning*, *31*, 462–480.

Wishart, J. (2001). Motivation and learning styles in young children with Down syndrome. *Down Syndrome Research and Practice*, *7*(2), 47–51.

Wishart, J. (2005). Children with Down's syndrome. Chapter 7. In A. Lewis, & B. Norwich (Eds.), *Special teaching for special children?* Berks: Open University Press.

Wishart, J. G., & Duffy, L. (1990). Instability of performance on cognitive tasks in infants and young children with Down's syndrome. *British Journal of Educational Psychology*, *60*, 10–22.

Yang, Y., Conners, F. A., & Merril, E. C. (2014). Visuo-spatial ability in individuals with Down syndrome: Is it really a strength? *Research in Developmental Disabilities*, *35*, 1473–1500.

Zhang, M. (2015). Understanding the relationships between interest in online math games and academic performance. *Journal of Computer Assisted Learning*, *31*, 254–267.

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