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Abstract: This study investigated the performance of 172 Grade 4 students (9 to 10 years) over a 12 month period on a 36-item test that comprised items from six distinct graphical languages (e.g., maps) that are commonly used to convey mathematical information. The results of the study revealed: 1) difficulties in Grade 4 students' capacity to decoding a variety of graphics; 2) significant improvements in the students' performance on these graphical languages over time; 3) gender differences across some graphical languages; and 4) the influence of spatial ability on decoding performance. The implications of this study include the need to support the development of students' ability to decode graphics beyond activities usually investigated in mathematics curricula.

Solving Graphics Problems: Student Performance in Junior Grades

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ABSTRACT The authors investigated the performance of 172 Grade 4 students (9 to 10 years) over 12 months on a 36-item test that comprised items from 6 distinct graphical languages (e.g., maps) commonly used to convey mathematical information. Results revealed (a) difficulties in Grade 4 students' capacity to decode a variety of graphics, (b) significant improvements in students' performance on graphical languages over time, (c) gender differences across graphical languages, and (d) influence of spatial ability on decoding performance. Implications of this study include the need for supporting development of students' ability to decode graphics beyond activities usually investigated in mathematics curricula.

Keywords: Grade 4 students, solving graphics problems, spatial reasoning

The importance of representation in teaching, learning, and understanding mathematics is widely acknowledged (e.g., Cucuo & Curcio, 2001). However, although our society uses a vast array of *information graphics* (e.g., graphs, diagrams, charts, tables, maps) to manage, communicate, and analyze information (Harris, 1996), researchers have given scant attention to the interrelationship between numeracy and representation (Pugalee, 1999). That relationship involves the ability of one to decode mathematical information from graphics and encode mathematical information into graphics (Baker, Corbett, & Koedinger, 2001; Diezmann, 2004).

The relative lack of attention continues even though the information-burgeoning society increasingly represents information through images and graphics. Research on the use and understanding of images is limited (Postigo & Pozo, 2004), despite the calls for this essential and increasingly important literacy (Balchin & Coleman, 1965; Lowrie, 2005; Zevenbergen, 2005). Postigo and Pozo (2004) argued that research conducted in the field is heterogeneous because the study of maps, diagrams, and numerical graphs has its own syntax and conventions. Similarly, Lowrie and Diezmann (2005) maintained that students need to become “code-breakers” to access the mathematical information in graphics that is used in tasks, texts, tests, software, and other everyday situations.

Our purpose in this article was to explore students’ ability to decode information graphics while considering the particular types of graphics used, students’ visual–spatial abilities, and gender. The justification for investigating these variables follows.

Categorization of Information Graphics

Visual representations, such as graphs, diagrams, charts, tables, and maps are part of the emerging field of information graphics. In mathematics, information graphics convey quantitative, ordinal, and nominal information through a range of perceptual elements (Mackinlay, 1999). Those elements include position, length, angle, slope, area, volume, density, color saturation and hue, texture, connection, containment, and shape (Cleveland & McGill, 1984). Although thousands of graphics are used, they can be categorized into six "graphic languages" (see Table 1) that link the perceptual elements with particular primary encoding techniques (Mackinlay, 1999). He explained that

> *Single position languages* encode information by the position of a mark set on one axis. A*pposed-position languages* encode information by a mark set that is positioned between two axes. *Retinal-list languages* uses one of the six retinal properties of the marks in a mark set to encode the information. Since the positions of these marks do not encode anything, the marks can be moved when retinal list designs are composed with other designs. *Map languages,* which have fixed positions, encode information with graphical techniques that are specific to maps. *Connection languages* encode information by connecting a set of node objects with a set of link objects. *Miscellaneous languages* encode information with a variety of additional graphical techniques. (p. 75)

Thus, students need to appreciate how the visual components and spatial organization of particular graphics affect the interpretation of symbols within a graphic. For example, relative position is important for one to determine the numerical value of missing numbers of a number line (Diezmann, & Lowrie, 2006). An example item for each of the graphic languages is included in Appendix A.

Difficulties in Interpreting Graphics

Some students find that certain graphics are difficult to decode. For example, on the National Assessment of Educational Progress (NAEP), many fourth graders had difficulty reasoning from a bar graph (National Center for Education Statistics [NCES], n.d.) and using a scale (NCES; see Table 2). The students' success on the scale item was no better than was chance accuracy (1 out of 4 students; 25%). Although eighth graders outperformed fourth graders on both items, many of the older students also had difficulty with graphics (see Table 2). The performance differences between the bar graph item (opposed position) and the scale item (axis) at each grade level indicated variance in the difficulty level of particular graphical languages. Wainer (1980) also reported differences in the relative difficulties of some graphics and increased success with age; however, that study investigated limited graphics.

Differences in student success on particular items and at different grades could be attributed to knowledge of embedded mathematics content in the question. However, the particular graphic used to represent information is a major factor in students' success. Baker et al. (2001) reported substantial variance in eighth- and ninth-grade students' ability to interpret "informationally" equivalent graphics with students' comparative success rates of 95% on a histogram, 56% on a scatterplot, and 17% on a stem-and-leaf plot. They argued that that performance variance was caused by students' transfer of knowledge about bar graphs to the other three graphics, and that although histograms and scatterplots share surface features with bar graphs, stem-and-leaf plots vary at the surface level from bar graphs.

In a substantial body of literature, researchers have indicated that even the most routine analysis of data that is embedded in graphics may be difficult for older children (e.g., Preece, 1993) and even university students (Goldberg & Anderson, 1989) to interpret. As Postigo and Pozo (2004) suggested, "Students restrict themselves to reading data and processing specific aspects of the material and encounter problems when they have to go beyond this elementary level and interpret the information represented" (p. 628). Hence, the successful solution of graphic problems requires that students (a) understand the mathematics content and (b) decode the particular type of graphic in which the mathematical information is embedded.

The Role of Visual–Spatial Abilities in Decoding Graphics

Decoding information graphics involves interpreting information presented in a visual–spatial format. Hence, decoding draws on spatial ability, which is a composite of abilities rather than a unitary construct, and includes mental rotation, spatial perception, and spatial visualisation (Voyer, Voyer, & Bryden, 1995). Some students may be predisposed to high or low performance on decoding tasks. For example, students who have high spatial ability may decode graphics with relative ease because of their enhanced ability to process visual information (Vekiri, 2002). Kozhevnikov, Hegarty, and Mayer (2002) found that students with high spatial ability (categorized as "visualizers" along a preference continuum) outperformed students with low spatial ability when solving time-position graphs (opposed-position languages). Those performance differences remained when controlling for other factors, including mathematical background, general intelligence, and the use of metacognitive strategies. Similarly, students who have visual perception or processing problems may experience particular difficulties decoding graphics (e.g., Zangemeister & Steihl, 1995).

By contrast, Postigo and Pozo (2004) examined the graphic information expertise required for adolescents to complete graph and map tasks and found that spatial skills were not a mediating variable in performance. They postulated that literacy and numeracy skills were more important than were special abilities with respect to task understanding and success. Nevertheless, researchers who reported contrary results (e.g., Zangemeister & Steihl, 1995) indicates that spatial ability is an aspect of reasoning that should be considered when conducting investigations involving graphical problem solving.

Gender and Spatial Ability

Many explanations for apparent differences between males and females on spatial tasks have emerged from the literature. Linn and Petersen (1985) stated, "Differences between males and females in spatial ability are widely acknowledged, yet considerable dispute surrounds the magnitude, nature and age of first occurrence of these differences"

(p. 1479). They reported that spatial perception and rotation tasks were easier for males than for females but that tasks characterized by an analytical combination of visual and nonvisual strategies were different for both genders.

Silverman and Eals (1992) and Saucier et al. (2002) found that with adult participants, males outperformed females on Vandenberg and Kuse’s (1978) mental rotation test; Saucier et al. found significant correlation between performance on the mental rotation test and better performance on certain navigational tasks. Mental rotation tasks focus on orientation, which is included in the retinal-list languages (see Table 1). Similarly, Voyer et al. (1995) found that the only gender difference in students aged under 13 years (which favored boys) was performance on mental rotation tasks. In an investigation into gender differences in young children’s spatial ability, Levine, Huttenlocher, Taylor, and Langrock (1999) reported a significant male advantage on spatial transformation and maze tasks.

However, meta-analyses conducted over time have revealed that although some of the gender differences are reliable, most are insignificant (Spelke, 2005). Hyde (2005) even suggested that 78% of all psychological gender differences are small or close to zero. In a comprehensive meta-analysis, Linn and Hyde (1989) found that gender differences in spatial ability declined over time. Considering the controversial nature of the issue, we decided that gender should be taken into account in this study, particularly in light of the age of the participants.

Method

This investigation is part of a 4-year continuing study designed to enhance understanding of the development of primary students' ability to decode information graphics representing mathematical information. We report a component of the study in which we seek to,

1. Determine the relationships between decoding performance across the six graphical languages;
2. Determine the influence of spatial ability on performance across the six graphical languages;
3. Document fourth-grade students' knowledge of particular graphical languages in mathematics; and
4. Establish whether there are gender differences in students' decoding performance in relation to the six graphical languages.

Participants

The 172 participants (88 girls, 84 boys) were selected randomly from six primary schools in a large rural city in Australia. Those included three Catholic schools, one private school, and two government schools. We selected fourth-grade students (aged 9 and 10) because other aspects of this study monitor these students' decoding performance over the last 3 years of their primary schooling. We analyzed these students' capacity to solve graphics problems over 12 months (while the students were in fourth and fifth grades). The participants were from varying socioeconomic and academic backgrounds and were not involved in any treatment program throughout the study—they continued with the mandatory curriculum of the state.

Instruments and Procedure

The Graphical Languages in Mathematics [GLIM] Test is a 36-item test (Lowrie & Diezmann, 2005) that determines students' decoding performance for each of the six graphical languages (see Appendix A for an example of each of the six graphical languages items). Initially, a bank of 58 items was variously trialled by the second author with primary-aged children (*N* = 796) in the state of Queensland, Australia to select items that (a) varied in complexity, (b) required substantial levels of graphical interpretation, and (c) conformed to reliability and validity measures. We selected the items from state and national year-level mathematics tests that had been administered to students in their final 3 years of primary school or to similarly aged students (e.g., Queensland School Curriculum Council, 2000).

A panel of five expert mathematics educators categorized independently each item within the framework (reliability coefficient 0.9). The educators then categorized the items within each language from pilot data as “easy,” “moderate,” and “difficult.” We removed questions with high literacy demands or responses with high variance from the pool. In its final form, the GLIM test comprised two items of each difficulty level within each language category. We administered the 36-item instrument to the students (*N* = 172) approximately 12 months apart in 2004 and 2005. The participants completed the instrument in approximately 50 min within intact classes (with class sizes between 24–31 students).

We administered the Raven's Standard Progressive Matrices (SPM; Raven, Raven, & Court, 1998, a subset of Raven's Progressive Matrices), to all the participants at the outset of the study to measure spatial reasoning. Participants completed the test in small groups in accordance with instrument protocol.

Results and Discussion

The findings for each of the four research aims are presented as follows:

1. *Relationships Between Decoding Performance Across Six Graphical Languages*

Initially, we determined relationships between students' decoding performance across the six graphical languages. The six graphical languages correlated positively with each other (see Table 3) in the 1st year of the investigation (when participants were in Grade 4). With the exception of the axis-opposed-position correlation (r = .15, $p \leq .05$), all correlations were statistically significant at $p \leq .01$. Nevertheless, even the strongest relationships [connections–maps (r = .39, $p \leq .01$) and miscellaneous–connections (r = .41, $p \leq .01$)] correlated only moderately with each other, despite the strong statistically significance. The connections–map and miscellaneous–connections correlations accounted for approximately 16% of the variance. The miscellaneous and connection categories had the strongest correlations with the other graphical language (with all correlations ≤ 0.27).

By contrast, the correlations between the retinal-list languages category and other language categories were somewhat weaker (most correlations less than 0.30). In most cases, the retinal-list items required participants to consider graphical features that included shape, size, saturation, texture, and orientation. Thus, decoding those graphics required an understanding of the use of perceptual elements to convey mathematical information. The weakest correlation was between the axis and opposed-position languages. Although both of those languages use axes, they differ substantially at a structural level with information encoded in only one dimension in axis languages and in two dimensions in opposed-positional languages (Mackinlay, 1999).

The relatively weak correlations may be attributed to the fact that the six types of graphical language appeared in an ordered sequence, whereas the six languages items occurred in sequence six times in the order axis, opposed-position, retinal-list, map, connection, and miscellaneous. Consequently, the participants did not become familiar with solving the same category of problem and may not have formed appropriate visual cues for “like” problems. When Aberg-Bengtsson and Ottoson (2006) attempted to identify factors that attributed to graphicacy test performance, they found that participants tended to successfully solve sets of tasks that had common conventions and symbol systems on the same page. Thus, if all of the axis graphical language items had been together, the students might have developed more refined mental representations. However, the separation of items of the same graphic language type limits the potential for the solution of one item to cue the solution to another item.

2. The influence of spatial ability on performance across the six graphical languages

We next determined the influence of spatial ability on performance of the six graphical languages. We conducted six multiple-regression analyses with spatial ability (measured by the Raven's SPM score) as the dependent variable. In each model, we entered gender as the first block, followed by the Grade 4 score, then the Grade 5 score for the respective graphical language. The procedure treats gender as a covariate, ensuring that any shared variance is removed from the model (and deemed necessary considering the attention given to studies involving spatial reasoning and gender). In each analysis, Grades 4 and 5 graphical language scores made a statistically significant contribution to the model after we accounted for gender. The dependent variable (see Table 4) accounted for more than 20% of the variance in four of the six models (retinal-list, .27%; map, .22%; connection, .21%; and miscellaneous, .26%). Those results are consistent with other studies in which researchers found that spatial reasoning is influential in problem solving (Kozhevnikov et al., 2002; Lowrie & Kay, 2001).

3. Performance of Participants in Grades 4 and 5

We next documented the participants' knowledge of particular graphical languages in mathematics over time (Grades 4 and 5). Table 5 shows the means and standard deviations for participant scores across the six categories (six items in every category, so 6 is the maximum score) and indicates significant improvements in the students' performance on the graphical languages over time.

The students more successfully completed the miscellaneous and map languages than the other four categories of graphics. The two types of graphical languages are explicitly taught in key learning areas outside the mathematics syllabus. By contrast, the mean score for the opposed-position category was considerably lower (15% and 12%, respectively, than the miscellaneous category), despite the concentration of activities involving line charts, bar graphs and histograms in the curriculum and in state numeracy tests (e.g., Queensland School Curriculum Council, 2000). The results indicate differences in the difficulty level of various graphical languages for Grades 4 and 5 students. Although some of the variance could be attributed to content, the particular graphical languages used are likely to be a major factor that influences student performance (Baker et al., 2001). The results are also consistent with a large body of literature (e.g., Larkin & Simon, 1987; Shah & Carpenter, 1995) that revealed that graphics that involve pattern perception and association are easier to interpret than are graphics that require logical inferences (connection languages), or spatial transformations (retinal-list languages). Moreover, the results support the notion that graphics that include information or ideas that have some form of *life-like* authenticity (many of the miscellaneous and map languages) allow students to engage in critical thinking that facilitates problem solving (Lowrie, 2005).

In addition, informal learning experiences in which Grades 4 and 5 students engage in through everyday activities (e.g., sport) affect their knowledge of particular graphics (Diezmann, 2005b). Explanations for improved performance with age in this study are important because Grade 5/6 students do not always outperform Grade 4/5 students on graphic items (Diezmann, 2005a).

We found statistically significant differences between students' Grade 5 and Grade 4 scores across all six graphical languages: miscellaneous, t (1, 171) = 2.88, $p \leq .001$, map, t (1, 171) = 8.02, $p \leq .001$, axis, t (1, 171) = 5.17, $p \leq .001$, opposed-position, t (1. 171) = 8.03, $p \leq .001$, connection, t (1, 171) = 5.43, $p \leq .001$, and retinal-list, t (1, 171) = 5.93, $p \leq .001$. Thus, the performance of participants across all six categories of graphs was significantly higher in Grade 5 than in Grade 4. The effect sizes for the respective analyses were generally moderate (see Table 5). The results support the findings of other studies showing that the graphic performance of adolescents (aged 12–16 years; Postigo & Pozo, 2004) and mapping skills of primary-aged children (aged 5–12; Liben & Downs, 1993) improved over time.

4. Gender Differences

Finally, we tried to establish whether there were gender differences in students' decoding performance in relation to the six graphical languages. The mean scores for the male students were higher than were those of the female students in all six categories in Grades 4 and 5 (see Table 7). We conducted analyses of covariance (ANCOVAs) to determine whether statistically significant differences existed between the performances of boys and girls across the six graphical language categories. The following assumptions for ANCOVA were met. Tests for the homogeneity of variance, for which we used the Lavene test for equality of variance, indicated that the assumption of homogeneity of variance was not violated because all interactions were nonsignificant ($p > .05$). With respect to internal consistency, measures for the reliability of the covariate produced Cronbach alpha coefficients between .81 and .83. The correlation of the gender and spatial ability variables was weak (r = .03, p > .05). Finally, the homogeneity of regression slope assumption was not violated because the interaction between each covariate and its respective dependent variable was not statistically significant (p > .05).

The covariate (performance of the Raven's test score) controlled for spatial ability. We found gender differences in Grade 4, $F(1, 171) = 2.21$, $p \leq .05$, and Grade 5, $F(1, 171) = 2.24$, $p \leq .05$]. Subsequent post-hoc analyses (with alpha levels adjusted to p = .008 with a Bonferroni correction method) of Grade 4 data revealed no statistically significant differences across the gender variable for five out of the six categories: opposed-position [t (1, 171) = .16, p = .69, MS = .05]; retinal-list [t (1, 171) = 1.67, p = .19, MS = 1.82]; map [t (1,171) = 1.84, p = .17, MS = 1.01]; connection [t (1, 171) = .91, p = .34, MS = .40]; and miscellaneous [t (1, 171) = .50, p = .47, MS = .01]. There was, however, a statistically significant difference between the mean scores of the male and the female students in relation to the axis graphical language [t (1, 171) = 12.2, $p \leq .001$, MS = 13.96, d = .59]. In relation to Grade 5 data, there were statistically significant gender differences across the axis [t (1, 171) = 10.16, $p \leq .002$, MS = 13.72, d = .54] and map [t (1,171) = 7.41, $p \leq .007$, MS = 5.46, d = .49] languages.

The other four variables were not significant at p = .05: opposed-position [t (1, 171) = .40, p = .57]; retinal-list [t (1, 171) = 1.31, p = .36]; connection [t (1, 171) = .91, p = .34]; and miscellaneous [t (1, 171) = 1.81, p = .20]. We did not anticipate gender differences for axis languages at either grade level because no mental rotation was required and the students were under 13 years of age (Voyer et al., 1995). Moreover, research undertaken by Liben and Downs (1993) revealed no gender differences when Grade 5 children completed a series of axis questions. However, those results are consistent with Hannula's (2003) findings of gender differences for Finnish students on a number line task (axis) that favors boys for fifth-grade (n = 1,154) and seventh-grade (n = 1,525). Nevertheless, Hannula's explanation that gender differences appeared to occur on tasks that were more difficult for students is inadequate for our study because axis items were the third easiest of the six graphical languages (see Table 6). The addition of a second graphical category with gender differences in the Grade 5 data is more easily explained. For example, Matthews (1984) found that boys from the age of 8 or 9 began to develop a broader understanding of mapping skills and possessed a more sophisticated understanding of spatial relationships than did girls.

Conclusions and Implications

The ability of students to decode information graphics is fundamental to numeracy. Our results reveal distinct differences in student performances across the six graphical categories. Many of the fourth-grade students had difficulty decoding the graphics used in each of the graphical languages; also, some languages were more difficult for students than were others. Although there were positive correlations among the six graphical languages, the strength of the relationships were only moderate. We suggest, therefore, that educators need to devote much attention to the specific graphics and images embedded in mathematics problems that contain pictures, diagrams, and graphs.

Our findings also revealed significant improvements in students' performances across all graphics categories over 12 months. The students were not involved in any treatment program during that time, and they simply continued with the regular mathematics curriculum. We speculated that participants' general literacy and quantitative literacy also improved over this timeframe—and as a result—this increase in mathematics capacity provided an additional knowledge base when solving the problems. Grade 4 and Grade 5 students found that the miscellaneous and map categories were easiest to solve, whereas the connection and retinal-list tasks were the most difficult to solve. The graphicacy content of the mathematics curriculum contained explicit teaching of the four languages that the students found most difficult to solve. Students in both grades had the most difficulty solving the retinal-list tasks, despite the concentration of activities that focused on transformation, reflections, rotations, and translations in the Grade 4 and Grade 5 syllabi.

Also in both Grades 4 and 5, the boys outperformed the girls in each of the six graphical languages. Furthermore, statistically significant differences emerged between the performances of boys and girls across axis and map languages. Those differences add to the research literature because they were evident after spatial ability was controlled for—generally an explanation for the stronger performance of boys across tasks that require high levels of spatial ability or visual reasoning.

The results of this study indicate five educational implications.

1. Classroom teachers should be conscious of explicitly teaching the various graphical languages to support the development of students' ability to decode information graphics. The explicit teaching will remain a challenge if teachers cannot identify the important elements (and differences) among the graphical languages (Lowrie & Diezmann, 2005).

2. Because of gender differences in performances on axis and map languages, teachers should provide girls with strategic support for activities that incorporate these languages.
3. Learning opportunities should be broad and include graphical languages that are typically used outside formal mathematics contexts (i.e., maps, miscellaneous) in addition to those explicitly incorporated into the mathematics syllabus (axis, opposed-position).
4. Where appropriate, educators should explicitly link graphical languages to facilitate cognitive transfer.
5. Educators should explicate the informational content of graphics used for instructional purposes to ensure that all students have access to the embedded mathematical information.

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