Integration of Weight and Distance Information in Young Children:

The Role of Relational Complexity

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Abstract

Young children's integration of weight and distance information was examined using a new methodology that combines a single-armed apparatus with functional measurement. Weight and distance values were varied factorially across the item set. Children estimated how far the beam would tilt when different numbers of weights were placed at different distances from the pivot. There was a developmental progression from non-systematic responding (3-year-olds) to responding based on a single variable, usually weight (4-year-olds) to responding based on integration of weight and distance (5-, 6-, and 7-year-olds). Individual analyses revealed additive and multiplicative integration rules in children aged from 5 years. Weight-distance strategy complexity increased with age and was associated with better performance on independent measures of relational processing, especially the more complex items. Thus weight-distance integration involves processing of complex relational information. The findings enhance the explanatory power of Relational Complexity theory as a domain-general approach to cognitive development.

Integration of weight and distance information in young children: The Role of Relational Complexity

The extent to which children attend to dimensions such as height, width, weight, and distance and the manner in which they use and combine dimensional information when making judgements have been of widespread interest to researchers of cognitive development (Anderson, 1996; Miller, 1973) and science education (Kuhn & Dean, 2005; Kuhn, Iordanou, Pease, & Wirkala, in press) where control of variables and evaluating the effects of multiple variables are important components of experimentation and scientific thinking in general (Zimmerman, 2007). The current research investigates 3- to 7-year-old children's integration of weight and distance information, but the results are potentially relevant to other quantitative dimensions.

Previous research has addressed children's weight-distance integration using the traditional two-armed balance scale apparatus in which different numbers of weights are placed at varying distances from the fulcrum. This two-armed apparatus is usually combined with the choice methodology in which children predict the balance outcome. They provide a categorical response by indicating whether the left side or the right side will tilt down or whether the beam will balance (e.g., Siegler, 1981). Children's responses to different problem types are examined to diagnose the types of rules they used. Less frequently, the two-armed apparatus is used in conjunction with functional measurement techniques based on information integration theory (Surber & Gzesh, 1984; Wilkening & Anderson, 1991). Children are told the values of three parameters (e.g., weight on the left side (W_L), weight on the right side (W_R), distance on the left side (D_L)) and then they estimate the value of the fourth parameter (e.g., distance on the right side (D_R)) that would make the beam balance. Weight and distance values are varied systematically across the item set, and children's quantitative estimates are analysed to reveal the extent to which they used weight information, distance information, and whether they integrated weight and distance information additively or multiplicatively. As will be explained, both approaches (as currently used) include features that limit their usefulness for examining weight-distance integration in young children.

In the current research, we used a new methodology consisting of the single-armed apparatus shown in Figure 1, combined with functional measurement. We examined the extent to which 3- to 7-year-old children use and combine weight and distance information to estimate how far the beam will tilt when different numbers of weights are placed on pegs at different distances from the pivot. Predictions about the complexity of weight-distance strategies, their emergence during childhood, and associations with independent measures of relational processing were derived from Relational Complexity theory (Andrews & Halford, 2002; Halford, Wilson, & Phillips, 1998).

On the traditional balance scale task using the two-armed apparatus, application of the torque rule yields correct responses on all problem types. In the torque rule, weight and distance are integrated multiplicatively. When $W_L \times D_L = W_R \times D_R$, the beam balances, otherwise the side with the greater value tilts down. Siegler (1981) characterized the development of balance scale understanding as a sequence of rules, culminating in the torque rule (Rule IV). Children first use Rule I, which involves comparing W_L with W_R ignoring distance. Rule II involves comparing weights (as in Rule I) followed by distance if W_L and W_R are equal. With Rule III, both weight and distance dimensions are considered, but difficulty is encountered on conflict problems where weight is greater on one side and distance is greater on the other, and neither weight nor distance dominates. On these problems, children either guess or use imperfect integrative strategies such as the addition rule (Siegler & Chen, 2002). Siegler's data showed that 5- and 6-year-olds used Rule I, and they could also be taught to use Rule II; 8- and 9-year-olds used Rule I, Rule II, or Rule III; 13-year-olds used either Rule III or the addition rule, as did older adolescents and adults. A minority of older adolescents and adults used Rule IV (Siegler & Chen). Thus research using the rule assessment approach suggests that integrative strategies, as reflected by the addition rule or the torque rule, are not used until 13 years of age. However, other findings suggest that younger children can integrate weight and distance information using a compensation strategy in which they recognise that balance can be maintained if an increase in weight (distance) on one side is offset by a increase in distance (weight) on the other side (Inhelder & Piaget, 1958; Surber & Gzesh, 1984). Marini (1984; cited in Case, 1985, p. 107) showed that children begin to use a compensation strategy at around 7 years of age and its frequency increases thereafter.

Halford, Andrews, Dalton, Boag, and Zielinski, (2002a) characterized the development of balance scale understanding in terms of the relational complexity of the strategies children used, to complement Siegler's rules. According to Relational Complexity (RC) theory (Halford et al., 1998) reasoning about variables and their interrelations imposes a cognitive load, which stems from the complexity of the relations involved, that is, the number of arguments or entities related in a single decision. Unary relations have a single argument as in class membership. For example, the fact that Fido is a dog is expressed as dog(fido). Binary relations have two arguments as in larger-than(elephant, mouse). Ternary relations have three arguments as in arithmetic arithmetic-addition(2,3,5). Quaternary relations such as proportion have four interacting components as in 2/3 = 6/9, whereas quinary relations entail five interacting components.

The weight strategy involves estimating tilt from weight values alone, thus tilt = f(weight). The distance strategy involves estimating tilt from distance values alone, thus tilt = f(distance). Each involves a univariate function, and univariate functions are binary-relational (Halford, 1993). More advanced integrative strategies combine values on weight and distance variables. The additive strategy involves summing the effects of weight and distance variables, thus tilt = f(weight + distance). The multiplicative strategy, which yields normatively correct solutions, involves multiplying the effects of weight and distance variables, thus tilt = f(weight × distance). Each entails a bivariate function and bivariate functions are ternary-relational (Halford, 1993). However the multiplicative strategy is not always used even by adult participants, who tend to favour strategies based on addition (Kuhn, 2005; Weir & Seacrest, 2000). RC theory proposes that this preference reflects the ease of decomposition, which reduces effective RC (Halford et al., 1998; Halford, Bunch & McCredden, 2007). The additive strategy is more easily decomposed because additive variables (by definition) do not interact. By contrast, multiplicative variables do interact because each variable modifies the effect of the other, and according to the Method for Analysis of Relational Complexity, this would prevent decomposition, and result in higher effective RC (Halford, Cowan & Andrews, 2007). If decomposition occurs, complexity and processing load will be reduced.

Halford, Andrews, Dalton et al. (2002a) hypothesized that strategies based on a single variable (weight only, distance only) should be possible for 2- and 3-year-old children, and strategies that combine weight and distance should be possible from 5 years of age. They found that children as young as 2 years of age accurately predicted balance scale outcomes when different numbers of weights were placed on the right and left sides at a fixed distance from the fulcrum. Following brief familiarization, they also accurately predicted balance scale outcomes when a fixed number of weights was placed on the right and left sides at different distances from the fulcrum. Thus they succeeded on these non-conflict problems in which either weight values or distance values varied while the other variable was held constant. Binary-relational weight and distance strategies were sufficient for success on these problems. That young children predicted the effects of weight before familiarization, and the effect of distance only after familiarization shows that complexity is not the only factor influencing which strategy will be used. Earlier success with the weight dimension might be due to more opportunities to learn about the downward pull of weights. This is an environmental factor, reflecting greater experience with the effect of weight. Despite their success on the non-conflict problems, 2- to 4-year-olds performed at chance level on conflict items, in which both weight and distance values on the left and right sides varied and neither weight nor distance information dominated. Success on these problems required integrative strategies in which weight information and distance information are combined either additively or multiplicatively. Only the older children (5- and 6-year-olds) succeeded on all problem types. This is consistent with evidence from other content domains (Andrews & Halford, 1998; 2002; Andrews, Halford, Bunch, Bowden & Jones, 2003; Bunch, Andrews, & Halford, 2007; Halford, Andrews, & Jensen, 2002b; Halford, Bunch et al., 2007; Halford. Cowan et al., 2007), where ternary-relational processing emerges around 5 years of age. This research, which was based on strategy complexity, demonstrated integration strategies at a younger age than the earlier research using the choice methodology approach, where there was little or no evidence that children integrate weight and distance information using strategies based on addition and/or compensation, prior to 7 years.

Proponents of information integration theory have claimed that the two-armed apparatus with choice methodology is not well suited to examining integration (Anderson, 1996) because integration is required only on conflict problems when simple binary comparisons do not lead to an acceptable response. Integration seems awkward in these approaches, but more natural in functional measurement techniques. Functional measurement research in other content domains showed that 5-year-olds (e.g., Anderson & Cuneo, 1978; Rulence-Paques & Mullet, 1998; Wilkening, 1979; Wolf, 1995) and even 3- and 4-year-olds (Cuneo, 1980; 1982) can combine information about two dimensions, therefore it seems plausible that this approach might also yield evidence of weight-distance integration in young children.

Functional measurement was employed in two weight-distance studies. Surber and Gzesh (1984) used a seesaw apparatus similar to the traditional two-armed balance scale. The parameter W_L, was a set of three weights with an attached drawing of a "grown-up" person sitting on the left side of the seesaw. The value for W_L was held constant at 1 adult throughout and was equivalent in weight to 3 children. $W_{R,}$ was also a set of one or more weights, each with a drawing of a child attached. The aim in each of three tasks was to estimate the value of one parameter (either D_L, D_R, or W_R) that would make the seesaw balance, given the remaining parameters. Participants were 5-, 7-, 10-, and 13-year-old children and adults. The 5-year-olds tended to rely solely on distance information, while ignoring weight whereas older children (from 7 years) and adults integrated weight and distance either additively or multiplicatively.

Wilkening and Anderson (1991) used a similar procedure. Three groups of children (aged 6,1 to 7,9; 9,4 to 10,11; and 12,4 to 13,4) and a group of adults participated. The task involved estimating the values of W_R (weight adjustment) or D_R (distance adjustment) required to make the beam balance. The weight adjustment task was not administered to the youngest group. On the distance adjustment task, the group-based analyses showed the linear fan patterns indicative of multiplicative rule for the three older groups, and an irregular pattern for the youngest group. The analyses based on individuals showed that the majority of participants in the older groups used either additive or multiplicative rules. Of the ten, 6- and 7-year-olds, six used weight only or distance only rules, one used an additive rule, one used a multiplicative rule and two children's responses were unclassifiable. Thus Surber and Gzesh's and Wilkening and Anderson's studies provided no strong evidence of integration prior to 7 years of age.

However, these findings might underestimate the extent to which children can integrate weight and distance information. Surber and Gzesh's (1984) procedures, while innovative, required participants to keep in mind that one adult was equivalent in weight to three children and this might have adversely affected younger children's ability to use weight information and integrate it with distance information. Wilkening and Anderson's (1991) weight adjustment task was also too laborious for the youngest children. In the current study we sought to eliminate extraneous difficulties by using a single-armed apparatus, as suggested by Wilkening (1988). This apparatus (Figure 1) should allow a more straightforward assessment of weight-distance integration than is possible with the two-armed apparatus. If so, weight-distance integration might be observed at a younger age than in the two published functional measurement studies.

Based on RC theory (Halford et al., 1998) we predicted that integrative strategies should be present from 5-years of age, whereas less complex, single variable strategies should be present in younger children. Previous research indicates that relational processing has some degree of domain-generality in that children who succeeded on ternary-relational items in one content domain were likely to succeed on ternary-relational items in other content domains also (Andrews & Halford, 2002; Andrews et al., 2003; Halford, Andrews, Dalton et al., 2002; Halford, Andrews & Jensen 2002). If so, then the complexity of children's strategies on the weight-distance task should be predicted by their performance on transitivity and class inclusion tasks, especially the ternary-relational items within these tasks. To our knowledge, no other studies have related weight-distance integration assessed using functional measurement to performance on other cognitive tasks.

Method

Participants

Participants were 129 children in five age groups. There were 26, 3-year-olds (*M* = 3;7); S.D. = 3.42 months); 26, 4-year-olds (*M* = 4;9; S.D. = 3.55); 26, 5-year-olds (*M* = 5;8; S.D. = 2.30); 26, 6-year-olds (*M* = 6;5; S.D. = 3.0); and 25, 7-year-olds (*M* = 7;3; S.D. = 3.26). Three children were friends of the research assistant. The remaining children were recruited from five childcare centers, preschools, and primary schools in the Gold Coast region of Queensland, Australia. The research received institutional ethics approval and parents provided written consent for the children to participate.

General procedure

Each child completed three tasks presented in counterbalanced order. Testing was spread across two sessions, each approximately 30 min in duration.

Weight-distance integration. The apparatus is shown in Figure 1. Three vertical pegs were positioned at distances one, two, and three steps from the fulcrum. A spring (not shown) was attached on the left side. When weights were placed on a peg the beam titled downward, and the arrow pointed to one of the animal pictures. Each animal corresponded to a quantitative value of tilt. Children were familiarised with the apparatus and its operation. There were six demonstration trials, which were repeated if the experimenter judged this to be necessary. Three trials demonstrated the effect of weight on tilt. Children predicted how far the beam would tilt when one, two, or three weights were placed on Peg 2. Three trials demonstrated the effect of distance on tilt. Children predicted how far the beam would tilt when two weights were placed on Peg 1, Peg 2, and Peg 3. During each trial, the beam was held in a horizontal position by a lump of Blu-tac securing the arrow to the scale. The relevant number of weights was placed on the relevant peg, and the child predicted the degree of tilt by naming or pointing to one of the animal pictures. The Blu-tac was then removed and children observed the actual degree of tilt of the beam. The demonstration trials were followed by 36 test trials comprising four replications of all possible combinations of weight (1, 2, 3) and distance (1, 2, 3) values. Children responded in the same way as in the demonstration phase, but no feedback was provided. The beam remained in the horizontal position.

Class inclusion. Inferences based on classification hierarchies require recognition of the asymmetric nature of the relations between a superordinate class and two (or more) subclasses (Markman & Callanan, 1984). The relations are asymmetric because all members of a subclass (e.g., dogs) are included in the superordinate class (e.g., animals), but the reverse is not necessarily true (i.e., not all animals are dogs). To recognise this asymmetry, the relations among a minimum of three classes (superordinate, subclass 1, subclass 2) must be considered; therefore complexity is ternary-relational (Halford, 1993). The Class Inclusion task was based on Andrews and Halford's (2002) adaptation of Hodkin's (1987) task. Each of the six displays of coloured shapes depicted an inclusion hierarchy. For example, for the display with five blue circles and two blue triangles, the superordinate class is "blue things", the major (more numerous) subclass is "circles" and the minor (less numerous) subclass is "triangles". For each display, there were three questions. Question A required comparison of the two subclasses (*Are there more circles or more triangles?)* and is binary-relational. Question C required comparison of the superordinate class and the major subclass (*Are there more blue things or more circles?)* and is ternary-relational. Question B required comparison of the superordinate class and the minor subclass (*Are there more blue things or more triangles?)*. Responses to Question B were used to estimate guessing on the task (Hodkin). The maximum score for binary- and ternary-relational items was 6.

Transitive inference. Transitive reasoning involves inferring A *R* C from premises A *R* B and B *R* C, where *R* is a transitive relation, and A, B, and C are the elements related. Determining the relation between A and C requires that premises A *R* B and B *R* C be integrated to form an ordered triple, A *R* B *R* C. Premise integration relates three elements, therefore it is ternary-relational (Halford, 1993). The task required transitive inferences about vertical spatial position. It was modelled on Andrews and Halford's (1998, 2002) modification of Pears and Bryant's (1990) procedure in which children build towers using coloured squares. Each premise display consisted of four pairs of coloured squares in which one colour was higher than another. For example, the premises blue above purple, red above blue, yellow above green, green above red, together define the unique top-down order, yellow, green, red, blue, purple. More generally, A > B > C > D > E, where A is the top position and E is the bottom position. Children used coloured squares identical to those in the premise displays to construct their towers.

The two practice trials familiarised children with using the premises (clues) to determine the vertical order of coloured squares, and ensured they realised that (i) the relation *higher than* could refer to squares in adjacent and non-adjacent positions (ii) a square could be inserted above, between, or below the squares already in place and (iii) they might need to look at more than one premise pair to determine the correct order. Binary- and ternary-relational test items were presented using similar procedures and instructions. All items required children to use premise information to construct their towers. The essential difference was that two premises had to be integrated in a single decision in the ternary-relational items, whereas in binary-relational items each decision involved a single premise. In the binary-relational items, children constructed a 5-square tower, beginning with an internal pair, either BC or CD (step 1) followed by D or B (step 2). This concatenation (chaining) strategy entails processing one binary relation at a time. One point was awarded for each correctly ordered initial pair and subsequent square.

The maximum score was 8. In the ternary-relational items, two squares corresponding to positions B and D were placed on step 1. Square C was placed on step 2. If the child integrated BC and CD into the ordered array BCD to conclude that B is *above* D, then the correct position of C should be obvious. Credit was given for items where B, D, and C were placed correctly. The maximum score was 8.

Results

Weight-Distance Integration task

Group based analyses. Tilt estimates were subjected to a 3 (weight: 1, 2, 3) × 3 (distance: 1, 2, 3) × 5 (age: 3-, 4-, 5-, 6-, 7-year-olds) analysis of variance (ANOVA) with weight and distance as within-subject variables and age as the between subjects factor. Huynh-Feldt corrections were applied where necessary. There were significant main effects of weight, $F(1.52, 188.89) = 168.71$, $p <$ 001; distance, $F(1.83, 226.85) = 22.86$, $p < .001$; and age, $F(4, 124) = 5.87$, $p < .001$. These main effects were modified by a significant Weight × Distance interaction, $F(3.79, 469.43) = 10.59$, $p < .001$; a significant Weight × Age interaction, $F(6.09, 188.89) = 11.04$, $p < .001$; and a significant Distance × Age interaction, $F(7.32, 226.85) = 3.53$, $p = .001$. These interactions were in turn modified by a marginally significant Weight × Distance × Age interaction, $F(15.14, 469.43) = 1.59$, $p = .071$.

Figure 2 depicts the patterns observed at each age. For 3-year-olds, the main effects of weight and distance were not significant. The Weight × Distance interaction approached significance, $F(4, 100) = 2.38$, $p = .057$; but it was not of an interpretable form. For 4-year-olds, there was a significant main effect of weight, $F(1.7, 42.61) = 33.60$, $p < .001$. Tilt estimates increased with number of weights. Neither the distance effect nor the Weight × Distance interaction approached significance. For 5-year-olds, there were significant main effects of weight, $F(1.63, 40.69) = 112.69$, $p < .001$, and of distance, $F(1.34, 33.46) = 8.29$, $p = .004$ and a significant Weight × Distance interaction, $F(4, 100) = 5.21$, $p = .001$. For 6-year-olds, there were significant main effects of weight, $F(1.45, 36.33) = 69.38$, $p < .001$, and distance, $F(1.36, 33.99)$

= 11.81, $p = .001$ and a significant Weight × Distance interaction, $F(4, 100) = 7.76$, $p < .001$. For 7-year-olds, there were significant main effects of weight, $F(1.09, 26.14) = 19.63$, $p < .001$, and distance, $F(2, 48) = 22.73$, $p < .001$ and a significant Weight × Distance interaction, $F(4, 96) = 9.12$, $p < .001$. For the 5-, 6-, and 7-year-olds, tilt estimates increased as weight increased and as distance increased and the interactions were of the diverging form that is consistent with a multiplicative strategy. The group-based analyses suggest a developmental progression from non-systematic responding at 3 years toward the normatively correct multiplicative strategy.

Individual response patterns. Each child's tilt estimates were subjected to a 3 (weight: 1, 2, 3) × 3 (distance: 1, 2, 3) ANOVA in which weight and distance were between-item variables. One such analysis was conducted for each participant. The criteria for the strategy classification were as follows. If the analysis yielded no significant main effects of weight or distance, and no significant Weight × Distance interaction ($p > .05$ for each), then the child was classified as using no strategy. If the main effect of either weight or distance (but not both) was significant ($p < .05$) and the mean tilt estimates varied in the appropriate direction, and the Weight × Distance interaction was not significant, then the child was classified as using a single variable (weight only or distance only) strategy. If both weight and distance effects were significant, but the Weight × Distance interaction was not significant, then the child was classified as using an additive strategy. If both weight and distance effects were significant and the Weight × Distance interaction was significant ($p < .05$) and it was of the diverging form, then the child was classified as using a multiplicative strategy.

The probability that children's responses would meet these criteria by chance alone was computed using standard probability formulae 1, 2, and 3 (Pagano, 1986).

Single variable strategy: $P(W \text{ or } D) = P(W) + P(D) – P(W \text{ and } D)$ (1)

Additive strategy: $P(W \text{ and } D) = P(W) \times P(D)$ (2)

Multiplicative strategy: $P(W \text{ and } D \text{ and } W\times D) = P(W) \times P(D) \times P(W\times D)$ (3)

P(W) is probability of a significant main effect of weight (.05), P(D) is probability of a significant main effect of distance (.05), and P(W×D) is the probability of a significant Weight × Distance interaction (.05). The computed probabilities were .0975 for the single variable strategies, .0025 for the additive strategy, and .000125 for the multiplicative strategy.

Table 1 shows the number of children classified as using each strategy at each age. Binomial tests were used to determine whether the frequencies in each strategy type were significantly greater than chance. Just two 3-year-olds used a single variable strategy, which is non-significant ($p = .26$). All other non-zero values were significant, highest $p = .0003$. Thus significant numbers of 4-, 5-, 6-, and 7-year-olds used single variable strategies. Of the 46 children who relied on a single variable, the majority (43) used weight. Just three children in the single variable group (one 4-year-old, one -5-year-old, one 7-year-old) used distance. Significant numbers of 5-, 6-, and 7-year-olds used additive and multiplicative strategies. Strategy type and age were significantly associated, $\chi^2(12, N = 129) = 65.80$, $p < .001$. The number of children using no strategy decreased with age. The number using additive and multiplicative strategies groups increased with age.

Relational processing tasks

Table 2 shows the mean numbers of correct responses for the binary- and ternary-relational items of the class inclusion and transitive inference tasks for each age group. Zero variance in some cells precluded use of ANOVAs, therefore nonparametric analyses were conducted. Wilcoxon signed rank tests showed that the ternary-relational items were significantly more difficult than the binary-relational items in the class inclusion, $Z = 8.46$, $p < .001$, and transitive inference, $Z = 9.69$, $p < .001$ tasks. Kruskal-Wallis tests revealed significant age effects on the binary-relational class inclusion items, $\chi^2(4, N = 129) = 64.80$, $p < .001$, binary-relational transitive inference items, $\chi^2(4, N = 129) = 16.60$, $p = .002$, ternary-relational class inclusion items, $\chi^2(4, N = 129) = 75.66$, $p < .001$, and ternary-relational transitive inference items, $\chi^2(4, N = 129) = 53.77$, $p < .001$. Binary-relational class inclusion and transitive inference items were positively correlated ($r = .214$, $p = .015$) as were the ternary-relational class inclusion and transitive inference items ($r = .566$, $p < .01$). Therefore a binary-relational composite score ($M = 12.96$; S.D. = 1.78) and a ternary-relational composite score ($M = 5.57$; S.D. = 4.63) were computed for each child by summing across tasks. These composite variables were used in subsequent analyses.

Associations between tasks

Strategy type was converted to an ordinal-scaled variable, weight-distance (WD) strategy complexity. Scores ranged from 0 to 3 reflecting the number of main and interactive effects that were significant in the individual ANOVAs. Children who used no strategy received a score of 0, those who used single variable, additive, and multiplicative strategies received scores of 1, 2, and 3, respectively. WD strategy complexity was positively correlated with age and with binary-relational and ternary-relational composite scores. In a multiple regression analysis, binary-relational composite, ternary-relational composite, and age together accounted for 37% of the variance in WD strategy complexity, Multiple $R = .61$, $F(3, 125) = 24.57$, $p < .001$. Much of the variance (30%) was shared. However age (4.71%, $p = .003$) and the ternary-relational composite scores (2.05%, $p = .045$) each contributed significant unique variance. The binary-relational composite scores did not. Thus, the binary- and ternary-relational composite scores reduced the age-related variance in WD strategy complexity from 34.81% (based on zero-order correlation) to 4.71%, thereby accounting for 86.47% of the age-related variance in WD strategy complexity. In addition, the ternary-relational composite scores accounted for a small but significant amount of variance independently of age and the binary-relational composite scores. Regression statistics are shown in Table 3.

Discussion

The current research investigated weight-distance integration in 3- to 7-year-old children using a single-armed apparatus combined with functional measurement. Children predicted how far a beam would tilt when varying numbers of weights were placed at different distances from the pivot. This new method was effective in detecting systematic responding in children aged 4 years and above. The group-based analyses indicated a developmental progression from non-systematic responding in 3-year-olds, to responding based on a single variable (weight) in 4-year-olds, to responding based on the integration of weight and distance in 5-, 6-, and 7-year-olds. The individual responses showed a similar pattern. Significant numbers of 4-, 5-, 6- and 7-year-olds used strategies based on a single variable (most commonly weight), and significant numbers of 5-, 6- and 7-year-olds used strategies in which weight and distance information was combined additively and multiplicatively. Thus our new technique revealed evidence of integrative strategies in children as young as 5 years. The entries in the rightmost columns of Table 1 show that additive strategy was more frequent than the multiplicative strategy at 5 and 6 years of age, but by 7 years the additive and multiplicative strategies were equally frequent. Thus an intuitive understanding of the torque rule was detected in children as young as 5 years of age. This is consistent with previous findings that ternary-relational processing emerges at round 5 years of age (Andrews & Halford, 2002) and with the RC analysis that additive and multiplicative strategies involve ternary-relational processing, but that the multiplicative strategy is resistant to decomposition, and is therefore more difficult.

The findings suggest earlier emergence of integrative strategies than was observed in most previous studies using the two-armed apparatus combined with the choice methodology, where compensation strategies, which require integration, began to emerge at around 7 years, but at a comparable age to Halford, Andrews, Dalton et al.'s (2002a) where 5- and 6-year-olds succeeded on conflict problems using either additive or multiplicative integrative rules. Whereas additive and integrative rules could not be distinguished in Halford et al's research, results of the current study using the single-armed apparatus with functional measurement technique detected both additive and multiplicative integration rules in children from 5 years of age.

Integrative strategies were observed at an earlier age in the current study than in two previous functional measurement studies using a two-armed balance apparatus. Surber and Gzesh's (1984) youngest group (5-year-olds) responded on the basis of a single variable (distance), whereas 5–year-olds in the current study integrated weight and distance variables. In Wilkening and Anderson's (1991) group of ten, 6- and 7-year-old children, only two (20%) used integrative strategies, whereas 23 (45%) of the 6- and 7-year-olds did so in the current study. The earlier emergence of integrative strategies in the current study might well reflect our use of a single-armed apparatus, and the more straightforward assessment that ensued.

Another potentially important difference between the current procedure and most previous research is that the relevance of weight and of distance to degree of tilt was explicitly demonstrated to children in the current study. This was also the case in Halford, Andrews, Dalton, et al., (2002) but it is not standard practice in studies using the two–armed balance apparatus with choice methodology. Previous research (Halford, Andrews, Dalton, et al.) suggests that most children already realise the relevance of weight, but few spontaneously recognise the relevance of distance. It is possible that our procedure facilitated weight-distance integration, by assisting children to notice the role of distance when they otherwise would not have done so. Children who do not realise the relevance of distance would not integrate weight and distance information. Notice however that although children of all ages were alerted to the effects of weight and distance, integration strategies were observed only in children aged 5 years and above.

It could be argued that demonstrating the effects of weight and distance constitutes a strength of our method, because it separates the demand of knowing the effects of the individual variables from the demand of integrating their effects. (Kuhn, 2007) has shown that children who can isolate the effects of individual variables do not always combine them.

The emergence of integrative strategies around 5 years might appear discrepant with other findings using functional measurement. Cuneo (1980) reported that 3- and 4-year-olds used an additive (height + width) rule to judge the area of rectangles, and that 3- and 4-year-olds use an analogous (length + density) rule when judging the number of beads in an array (Cuneo, 1982). In Cuneo's tasks the quantities to be estimated (area, numerosity) were present in the stimulus displays. Children could perceive the quantities directly. In the current study, children had direct access to weight and distance values, but the degree of tilt had to be computed.

The cross-task results showed that children's performance on the relational processing tasks (class inclusion, transitive inference) was related to the complexity of their weight-distance strategies. Binary-relational and ternary-relational composite scores accounted for a large proportion of the age-related variance in strategy complexity. Furthermore, ternary-relational composite scores accounted for variance in strategy complexity independently of age and binary-relational composite scores. This is consistent with the relational processing hypothesis and the view that children's use of weight-distance strategies is constrained by task complexity. The cross-task findings replicate Halford, Andrews, Dalton, et al., (2002, Experiment 3) in which ternary-relational class inclusion and transitive inference items predicted children's performance on conflict balance scale problems over and above the binary-relational items. Thus findings from these two studies using different methodologies converge to suggest that weight-distance integration involves complex relational processing.

The weight-distance integration tasks and the transitivity and class inclusion tasks used in the current study have little or no similarity in terms of their surface characteristics (content, procedures) but according to RC theory they are equivalent in their complexity. Therefore, the cross-task findings support our complexity analysis of weight-distance integration. These cross-tasks results add to previous findings (Andrews & Halford, 2002; Andrews et al., 2003; Halford, Andrews & Jensen, 2002) that children who succeed on ternary-relational items in one content domain usually succeed on items of similar complexity in other content domains. These findings suggest that processing of complex relational information is a domain-general ability that undergoes considerable development between 3 and 8 years of age.

To conclude, we have developed an improved method for examining weight-distance integration in young children. This method revealed systematic responding in children as young as 4 years of age, and evidence of additive and multiplicative integration rules in children aged 5 years and above. These results for the weight-distance integration task and the cross-task findings are consistent with the relational processing hypothesis derived from RC theory. RC theory is therefore capable of accounting for performance on the weight-distance integration task, and this enhances its explanatory power as a domain-general approach to cognitive development.

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Table 1

Number of children using no strategy, weight only or distance only, additive and multiplicative strategies by age group.

Age Group		Strategy Type			
	n	None	Weight only or distance only	Additive	Multiplicative
3-year-olds	26	24	2	0	0
4-year-olds	26	15	11***	0	0
5-year-olds	26	4	13***	7***	2***
6-year-olds	26	4	11***	8***	3***
7-year-olds	25	4	9***	6***	6***
		51	46	21	11

*** $p < .001$.

Table 2

Mean number of correct responses (standard deviations) for the binary-relational and ternary-relational class inclusion and transitive inference items by age

Age	Class inclusion		Transitive inference	
	Binary (max = 6)	Ternary(max = 6)	Binary (max = 8)	Ternary (max = 8)
3-year-olds	3.38	-0.77	7.35	0.77
	(1.50)	(1.63)	(1.44)	(0.99)
4-year-olds	4.77	0.96	7.96	2.38
	(1.63)	(2.13)	(0.20)	(1.84)
5-year-olds	5.54	2.38	7.88	3.42
	(1.03)	(3.06)	(0.59)	(1.23)
6-year-olds	6.00	4.54	8.00	4.23
	(0.00)	(1.58)	(0.00)	(2.08)
7-year-olds	5.96	5.60	8.00	4.52
	(0.20)	(0.65)	(0.00)	(1.96)

Table 3

Standard multiple regression of relational processing composite variables and age on weight-distance strategy complexity.

	Weight-distance strategy complexity	Binary-relational composite	Ternary-relational composite	*B*	β	sr^2 (unique)
Binary-relational composite	.43			.027	.051	
Ternary-relational composite	.56	.61		.049*	.240	.021
Age	.59	.62	.79	.246**	.366	.047

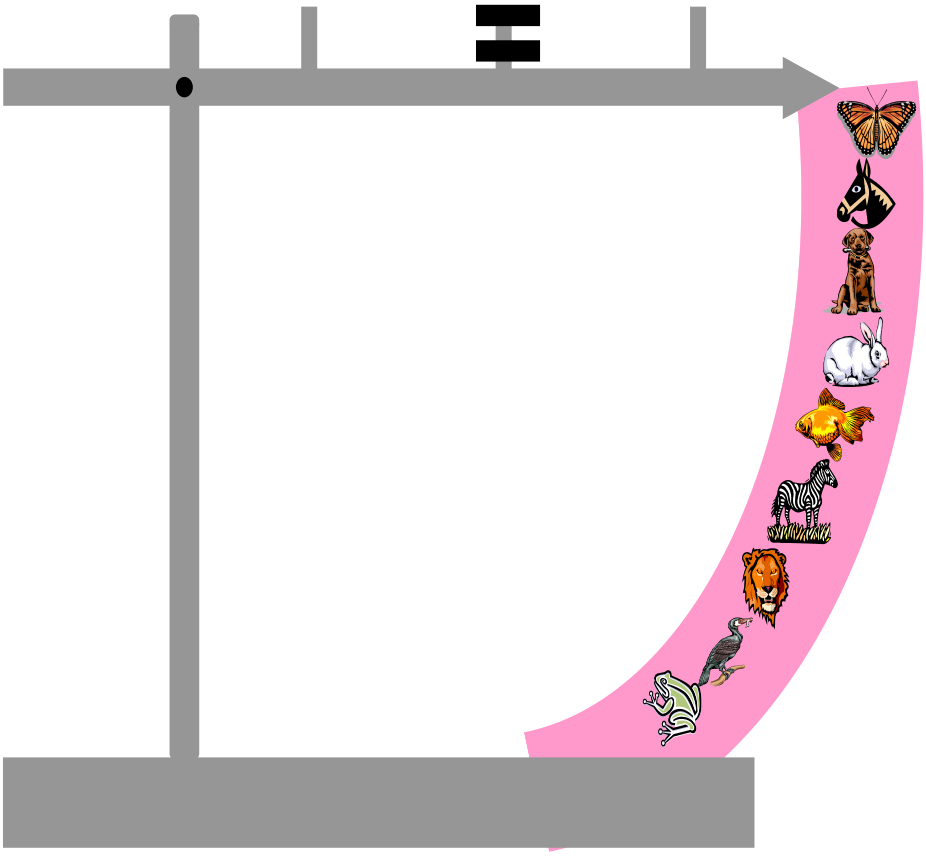
* $p < .05$.

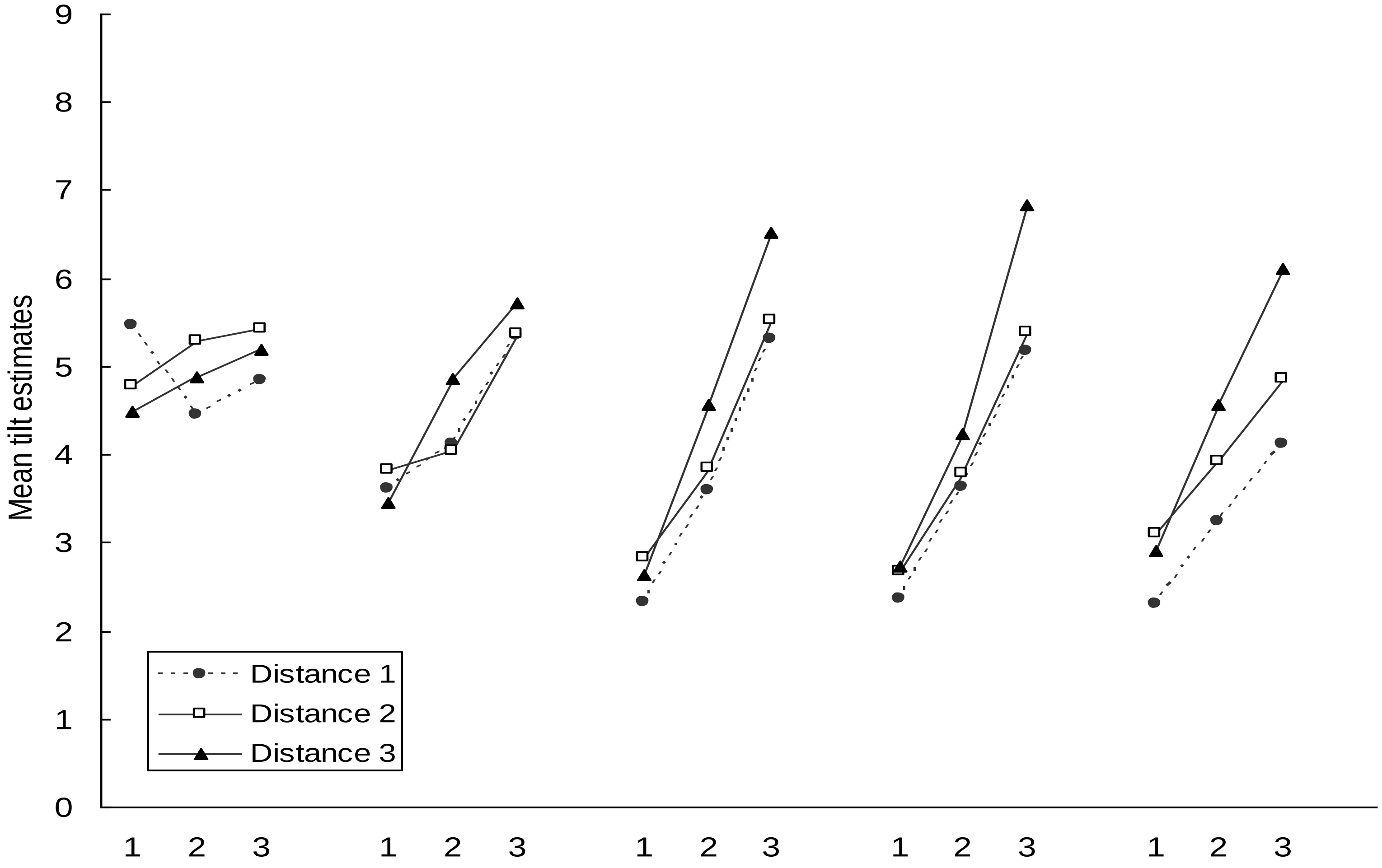
** $p < .01$.

Figure Captions

Figure 1. Apparatus for the weight-distance integration task (spring is not shown).

Figure 2. Tilt estimates as a function of weight and distance for 3-year-olds, 4-year-olds, 5-year-olds, 6-year-olds, and 7-year-olds.





Mean tilt estimates
9
8
7
6
5
4
3
2
1
0
Distance 1
Distance 2
Distance 3
1 2 3
1 2 3
1 2 3
1 2 3
1 2 3