The bicycle drawing test: mechanical reasoning and/or visual-spatial abilities?

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The Bicycle Drawing Test (BDT) is a measure of mechanical reasoning and visual-spatial and graphic functions. An adequate validation of the coding criteria of this test is still lacking. Aims of this work are: 1. to check the reliability of the scales by Greenberg, Rodriguez e Sesta (1994); 2. to explore other possible dimensions; 3. to compare the drawing and the copying task, in order to study the cognitive processes involved in each mode of execution. BDT (drawing and copying) was administered to 326 children from 7 to 10 years old.
None of the categories proposed by Greenberg, Rodriguez e Sesta (1994) reached a sufficient Cronbach's α. With item analyses and explorative factor analyses we found three dimensions: Mechanical Reasoning (MR), Fine Pictorial Skill (FPS), Spatial Organization (SO). Separate ANCOVAs were used to compare MR and SO by sex and age, including a covariate: an index of visual-motor control, i.e. the sum of the only five items in which the scores were higher in the drawing than in the copy (belonging all to the FPS scale). In sum, our preliminary analyses showed that some items of the Greenberg's coding are not discriminative, and the remaining items have a different dimensionality. Our subsequent analyses showed that the BDT can measure efficiently mechanical reasoning and spatial organization, without significant interference of visual-motor control.
Key words: *Bicycle Drawing Test*, *mechanical reasoning*, *visual-spatial abilities*, *copying*.

1
Drawing and cognitive assessment

The figurative drawing has become a popular tool for cognitive assessment since the seminal work of Florence Goodenough (1926). In fact, depiction requires several cognitive skills (Lange-Küttner, Vinter, 2008): motor and visual-spatial skills (Toomela, 2002); working memory (Morra, 2008); long term memory (Goodnow, 1977); problem solving skills (Freeman, Cox, 1985). Several studies have found connections between these abilities and other cognitive performances at various ages: e.g. Sortor and Kulp (2003) demonstrated a strong relationship between visual-motor coordination and reading/writing and mathematical abilities of children; Cahn *et al.* (1996) found a correlation between graphics tasks and the results of batteries for the assessment of dementia.

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2
The Bicycle Drawing Test

Pictorial tests are based on a variety of objects: the human figure (Goodenough, 1926; Harris, 1963), the clock (Shulman, 2000), the house (Ska, Désilets, Nespoulous, 1986) and, last but not least, the bicycle (van Sommers, 1989). The interest in this latter object as a pictorial theme dates back to the Piagetian studies on space representation (Piaget, Inhelder, 1956) and mechanical causality (Piaget, 1930). In 1959, thanks to the work of Taylor, the Bicycle Drawing Test (BDT) became a measure of visual-spatial and graphic functions, besides mechanical reasoning (Lezak, 1995). In fact, to successfully draw a bicycle involves different skills, whose full mastery goes beyond childhood. The understanding of movement transmission, difficult even for adults (Lawson, 2006), is interwoven with the pictorial competence needed to represent it: at the *ideational level* we need to imagine the movement (e.g. to avoid errors in the connection of the front wheel, which must be free to steer) and to access the rules of perspective (e.g. in a canonical, side presentation of a bike, the handlebar and the pedals, should "pierce the sheet"); at the *executive level* it is necessary to plan the sequence of signs in order to keep the entire object within the spreadsheet boundaries, and to successfully manage the connection and the proportion of its parts; finally, at the *visual-motor level* one should have a good control of the pencil to draw small details such as the chain or the pinion, or to properly orient and adjust the spokes. Studies involving clinical populations of adults (Schmitt *et al.*, 2009), or children with ASD and cognitive borderline (Levi, Penge, Iacovelli, 1990) support the use of the BDT in the neuropsychological screening (Diederich, Merten, 2009; Lezak, 1995), developmental assessment (Tavano *et al.*, 2007) and verification of treatments effectiveness in patients with brain damages (e.g. Sandyk, 1998).

The BDT offers the advantage of relying on a complex, yet familiar object: even young children know what a bicycle is and adults with various types of pathologies are not at odds with the idea of drawing it. The test is sufficiently independent from education and culture, except for the gendered interest for vehicles and mechanical objects (Alexander, Wilcox, Woods, 2009; Cherney, London, 2006), which in turn improves the males performance in the visual-spatial tasks (Linn, Petersen, 1985).

3
Psychometric properties

Despite the widespread use and longevity of the BDT, an adequate validation of the coding criteria is still lacking (Boone, 2012). The most recent contribution we were able to find dates back more than twenty years ago, when Greenberg, Rodriguez and Sesta (1994) revised the coding system by Lezak (1995) to make it sensitive to clinical cases.

Based on the performance of 75 children and adolescents with different neuropsychological disorders these authors devised 4 categories of items: Parts/Complexity (PC: presence-absence of constituent parts; 7 items); Motor Control (MC: proper execution of lines and psychomotor regulation; 5 items); Spatial Relations (SR: symmetry, proportions, correct locations of the parts, coherent orientation, correct planning within the sheet; 9 items); Mechanical Reasoning (MR: representation of the movement transmission; 5 items). Two studies with the new coding system showed: 1. that the scores in all the categories improves with age, especially after 10 years, while the boys superiority appears only in the Mechanical Reasoning; 2. that the test discriminated between children with cerebral palsy and other kind of pathologies. Greenberg, Rodriguez and Sesta (1994) found a good inter-rater agreement, a sufficient test-retest correlation, and a high correlation with the Bender Visual-Motor Gestalt Test (Koppitz, 1964) and the WISC-R (Wechsler, 1974). Construct validity, however, was more problematic: in the absence of a reliable factor analysis, the authors used exclusively item-total correlations, finding that, by and large, each item correlated with the total of its category, and not with other categories. For the authors' own admission, this grouping has various critical issues: from the conceptual trouble in the attribution of some items to their category, to the low intra-category correlation of the item relating to Motor Control, to the correlation between some items and the totals of other categories beside their own. In short, the proposal of Greenberg, Rodriguez and Sesta (1994) allows Schmitt *et al.* (2009) to conclude that BDT is a good measure of general cognitive functioning, but its drawback is not to allow an assessment of specific cognitive domains.

4
Drawing and copy

Typically, BDT simply requires to draw a bicycle without the driver: the subject is thus free to choose the model to represent, its size and proportions, as well as its right or left orientation, and its placement in the sheet. Only few authors have added the request to copy a drawn bicycle (i.e. Hubley, Hamilton, 2002; Levi, Penge, Iacovelli, 1990). The comparison between drawings and copies provides information on the cognitive processes involved in each mode of execution (Sandyk, 1998; van Sommers, 1989). Both tasks require the activation of visual-motor processes, but in the copy the imaginative component of the task is eliminated (Bouaziz, Magnan, 2007), while the artist is forced to deal with a new image, and to analyze it in order to draw each part one after the other, a task that requires a specific expertise (Tchalenko, 2009). A study conducted on adults with functional magnetic resonance imaging (Ferber *et al.*, 2007) has confirmed that the activities of copying and drawing activate different brain regions: the left lingual gyrus and cuneus (for the visual processing and the cross-modal attention in the copy), the anterior cingulated (for the motor control and the connection between intention with action in the drawing without a model). For these reasons, a combination of a drawing and a copying task could allows to distinguish the imaginative component from the perceptual-motor component, and provide useful information on the different skills underlying the pictorial performance.

5
Aims and hypotheses

To begin with, we will check the reliability of the scales by Greenberg, Rodriguez and Sesta (1994), and we will explore other possible dimensions underlying the overall performance of primary school children in the BDT. Comparing the drawing and the copying task, we will then verify which items are more difficult to copy than to draw: the examination of the performance in the drawing task, net of the skill shown in the copy, should provide better information on the reasoning and visual-spatial skills involved in the BDT. Overall, boys would perform better in the test dimensions related to spatial and mechanical reasoning; girls, instead, should perform better in the aspects requiring fine pictorial skills (Lange-Küttner, Kerzmann, Heckhausen, 2002). According to the developmental findings by Case (1992) and Morra (2008), older children should be significantly better in the mechanical and spatial reasoning; we do not expect age differences in motor control, which should be mastered well enough at the considered ages.

6
Method

Participants. Three schools were selected in three different cities of central Italy (a small, a medium-size and a big city); no special programs for pictorial abilities, besides the typical drawing activities, were conducted in these schools; in particular the representation of a bicycle had never been proposed as a school activity. The 326 families who provided a written consent to their children's participation were distributed as follows for the parents education: low level (elementary or middle school: 15%); medium level (high school: 54%); high level (university degree or more: 31%). Two age groups will be compared: 7-8 years olds (70 M, 81 F; mean age: 91 months) and 9-10 years olds (81 M; 94 F; mean age: 116 months). There were no clinically referred children.

Procedure. Each child was asked to draw a bicycle "as best as you can" in a sheet A4 with the long side horizontal (Drawing task, D). Then the child was given another sheet (identical for size and orientation) and required to copy a bike from a realistic drawing (Copying task, C). In both cases only the pencil was available, and to cancel was not permitted.

Scoring. The system by Greenberg, Rodriguez and Sesta (1994) requires to assign a 0-1 score to each of 26 items. All drawings (D and C condition) were scored by two trained raters, with an agreement ranging from 86% to 100%. Cases of disagreement were solved by the first authors of this paper.

7
Data analysis

First, for both the D and C drawings, we applied the Cronbach α to the four categories proposed by Greenberg, Rodriguez and Sesta (1994).

The items of the D drawings were then subjected to descriptive analyses, in order to eliminate those with very asymmetrical distributions. The items with acceptable psychometric characteristics were subjected to an exploratory factor analysis, with the method of principal components and orthogonal rotation Varimax (since the factors were not correlated). The scalar reliability of factors was evaluated by means of Cronbach α.

Each item in the C condition was compared with the corresponding item of the D condition using the Student's T, and the items in which the C score was significantly lower than the D score were summed to create an Index of Visual-motor Difficulty (VDI).

The scores in the scales identified by factor analysis were then compared for age and gender using a 2 x 2 ANCOVA (sex by age), in which the VDI has been added – when possible – as a covariate.

8
Results and discussion

Scalar properties of the Greenberg, Rodriguez and Sesta categories. None of the categories proposed by Greenberg, Rodriguez and Sesta (1994) reached a sufficient Cronbach's α (D condition: PC = 0.192; MC = 0.174; SR = 0.346; MR = 0.574; C condition: PC = 0.217; MC = 0.077; SR = 0.429; MR = 0.414). The proposed grouping appears inadequate not only for Motor Control, as noted by the authors themselves, but also for the Parts/Complexity and for Spatial Reasoning; only the Mechanical Reasoning is not far from an acceptable level in the D condition.

Factor analysis of the D task. Two items (wheels and handlebars) were eliminated because of no variance; other five items (saddle, spokes, position on the sheet, connections, no perseveration) were also excluded because had very high kurtosis and skewness. An initial factor analysis on the remaining items yielded 8 factors, explaining 64.62% of the variance. Only the first four factors, however, appeared to have adequate scalar characteristics. In the light of this result, we excluded the items belonging to the four last factors (Pedals; Junctions; No useless lines; No tremor; Wheels without angles; Wheels of the same size; Width). A new factor analysis on the remaining items yielded 4 factors with Eigenvalue > 1, and a variance explained of 60,0%.

The Factor 1 ($\alpha = 0.72$) measures the Mechanical Reasoning (MR) since it includes the three main components of the movement transmission (items: 6. Gear assembly; 23. Pedal connected to the wheel sprocket; 24. Chain connected to rear wheel center), two of which were considered by Greenberg, Rodriguez and Sesta (1994) as indicative of the same dimension. However our factor does not include the frame-wheels connections, probably for their specific pictorial difficulties (see later). On the other hand, the factor includes the representation of the chain and the toothed wheel, which cannot be omitted without preventing the bike functionality.

The Factor 3 ($\alpha = 0.72$) consists of three items (14. Symmetrical wheels; 15. Symmetrical spokes distribution; 16. Similar and appropriate distribution of spokes within each wheel) belonging to the category of Spatial Relationships in the original system. However, unlike other components of this category, these three item require a particular effort of visual-motor control to make the round wheels and to properly arrange the spokes. We labeled this factor Fine Pictorial Skill (FPS).

The Factor 2 hade a high α (0.87) but consisted of only two items with negative factor loadings; Factor 4 had an insufficient α (0.47). These two factors were combined into a single scale because they both require advanced skills in the pictorial representation of space. In fact, Factor 2 includes the items 25 and 26 that require an overlapping of lines to represent the connections between each fork and each wheel: as mentioned above, the overlap of lines, implying the amodal presence of an object behind another, is an advanced pictorial skill, according to many scholars of children's drawings (Goodnow, 1977). On the other hand, the items of Factor 4 (7, 17, 21 and 22) imply in various ways the maintenance of a single point of view for all the parts, an ability recognized since the earlier studies of children's drawings (Luquet, 1927) as the main pictorial progress in the middle childhood. In particular, the correct drawing of the handlebar and the representation of the pedals introduces depth in the drawing, and affects the unified orientation of the parts.

Combining the two factors we obtain a scale with a satisfactory α (= 0.62), which measures the Spatial Organization (SO) with the following items: 7. Complete frame, 17. Similar orientation of the parts, 21. Correct proportion and relation of the parts, 22. Handlebar allows steering control, 25. Connection of front wheel with front frame, 26. Connection of rear wheel with rear frame.

Comparison of drawing and copying. In almost all of the items there are significant differences between drawing and copying, with higher scores in this latter task. Only five items have significantly or tendentially lower scores in the copy: 11. No line tremor; 19. All parts connected; 12. Wheels without angles; 13. Wheels of same size; 14. Symmetrical wheels. These items coincide in part with those forming the above described scale FPS. Thus the IDV calculated by summing the scores on these 5 items will be added as a covariate only in the ANCOVAs on MR and SO.

Comparisons by age and gender. The comparison by age and gender on the scores of MR and SO showed no effect of the covariate (IDV). The Mechanical Reasoning varies with age in favor of the older children (0.68 vs. 0.42, $F_{1, 322} = 8.43$, $p < 0.01$) and with gender, in favor of boys (0, 84 vs. 0.31, $F_{1, 322} = 33.19$, $p < 0.001$). SO also improves with age (1.5 to 1.96) ($F_{1, 322} = 7.3$, $p < 0.01$) and is higher in boys (2.01 vs. 1.54) ($F_{1,322} = 8.97$, $p < 0.01$). It should be noted that the boys advantage on this scale depends on their score in the two items of Factor 2 (connection between the pins and the wheels) requiring attention to the mechanism of the bicycle as well as expertise in the representation of spatial relations. These results are then substantially consistent with those of Greenberg, Rodriguez and Sesta (1994) with regard to mechanical reasoning.

Finally, in the scale of Fine Skill Pictorial we find a slight but significant ($F_{1,322} = 6.39$, $p < 0.05$) improvement with age (from 2.36 to 2.59) and no gender effect, thus disconfirming our hypothesis of an advantage for girls. The lesser interest for the task may explain this result: in fact the vehicles appear less frequently in spontaneous drawings of girls than in those of boys (Picard, Boulhais, 2011).

9
Conclusions

Overall, the first part of this study: *a*) suggests to avoid a separate examination of the number of parts introduced, since some of them are universally present (wheels and handlebars) or almost universally present (saddle and spokes), while others requires specific skills, better measured by other scales; *b*) entrusts the assessment of mechanical reasoning solely to the depiction of the movement transmission; *c*) distinguishes the fine visuo-motor abilities from higher-order painting skills related to the space representation and to the drawing third dimension. The subsequent analyses show that the bicycle drawing can measure efficiently some higher cognitive abilities (mechanical reasoning and spatial organization), without significant interference of visual-motor control. The negative spread between drawing and copying in some items is a candidate to become a most reliable test of this skill, but it is a limitation of the present study not to have yet identified, for the copy, a real scale with adequate psychometric properties. We hope that this study would support the development of a simpler, yet more informative coding system, than that proposed by Greenberg, Rodriguez and Sesta (1994), making the BDT a more useful tool in the first neuropsychological assessment. However, this study should be replicated with a larger sample, in order to allow a finer age analysis, also extending the survey to one or more clinical groups of children with disorders that affect the neuropsychological functions in various ways, particularly in the visual-motor and visual-spatial area.

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Riassunto

Il Bicycle Drawing Test (BDT) è uno strumento di valutazione del ragionamento meccanico e delle abilità grafiche e visuo-spaziali che a tutt'oggi non possiede un sistema di codifica adeguatamente validato. L'obiettivo del nostro lavoro è: 1. verificare l'affidabilità delle scale proposte da Greenberg, Rodriguez e Sesta (1994); 2. esplorare altre possibili dimensioni misurate dal BDT; 3. confrontare le prestazioni ai compiti di disegno a memoria e su copia per comprendere i processi cognitivi coinvolti nelle due modalità esecutive. Il BDT (disegno e copia) è stato somministrato a 326 bambini dai 7 ai 10 anni.

Nessuna delle categorie proposte da Greenberg, Rodriguez e Sesta (1994) ha ottenuto una sufficiente α di Cronbach. Attraverso un'analisi degli item e un'analisi fattoriale esplorativa abbiamo trovato tre dimensioni: Ragionamento meccanico (MR), Abilità pittoriche fini (FPS), Organizzazione spaziale (SO). Sulle scale MR e SO sono state eseguite due separate ANCOVA aventi per variabili indipendenti il genere e l'età e per covariata un indice di controllo visuo-motorio, dato dalla somma dei cinque item (tutti appartenenti alla scala FPS) in cui i punteggi sono risultati maggiori nel disegno rispetto alla copia. Le nostre analisi preliminari hanno mostrato che alcuni item del Sistema di codifica proposto da Greenberg non discriminano, e che i restanti item hanno una diversa dimensionalità. Le analisi successive hanno mostrato che il BDT può misurare in modo efficace il ragionamento meccanico e l'organizzazione spaziale, senza un'interferenza significativa del controllo visuo-motorio.

Parole chiave: *Bicycle Drawing Test*, *ragionamento meccanico*, *abilità visuo-spaziali*, *disegno su copia*.

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