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A method for a cognitive analysis of graphical presentations

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Abstract

The present study examines how some properties or relations embedded in propositions can be represented iconically, and suggests a method for coding and analysing such representations according to the semantic properties of situations that are expressed. A method for assessing communicative effectiveness is also sketched.

1. Introduction

The benefit of graphical presentations (drawings, diagrams, graphs, etc.) as a powerful tool in several cognitive tasks (mathematical learning, reasoning), or as a communication aid in scientific, instructional or technical fields, or in web-based instruction, is well known (Sierpinska, 1992; Lesh, Behr, & Post, 1987; Mayer, 2003; Schnotz & Bannert, 2003; Gagatsis & Elia, 2004). Their efficacy is traditionally not questioned ("a diagram is worth ten thousand words", Larkin & Simon 1987). Recently, however, this belief is being considered more critically, because how these supposed beneficial effects are produced is still unclear.

Some relevant data in cognitive tasks are abstract and can hardly be translated into a graphic format. Therefore, drawings are normally enriched with words, numbers, captions or other symbolic elements, which express information that cannot be conveyed by a simple drawing. The problem of representation of abstract properties in a pictorial format is specially relevant when dealing with instructional material (cfr. graphic organizers: Robinson & Kiewra, 1995; Robinson, 1998).

This enrichment is not just addition but integration, because what is added, where it is put, what information is given, are crucial aspects. The question is, then, how cognitive representations of pictures and other symbols interact in order to convey meaning. In particular, the case of the integration of verbal and pictorial elements deserves a special interest, along with studies about the cognitive properties of such two kinds of representation.

According to some scholars, the use of both verbal and pictorial elements is always beneficial (Mayer, 2003); but according to others this is not the case, either because of a possible cognitive load (Sweller, 1988; Sweller, van Merriënboer & Paas, 1998) or a possible interference between the two kinds of information (Schnotz & Bannert, 2003). Such question, in fact, is still unanswered. For example, according to the "spatial contiguity effect" (Mayer, 2003), learning is easier when words are spatially close to pictures, but it is not explained why. It seems hardly plausible that it might work just because both verbal and pictorial elements are present.

Many theories make reference to "mental integration". The most usual explanation of integration, in the vein of the Paivio's dual coding theory, is that the two kinds of information are processed differently, giving rise to different mental models. The integration would be the result of a mapping of elements of one model into the other, or of some dynamic process like skipping back and forth between text and picture.

Existing models, however, only account cognitive processes used to take advantage of graphic displays, but not processes used to construct pictorial representations by translating conceptual representations into a propositional format, and not how this construction is done according to the demands of different situations. Most research has been conducted about how ready-made presentations (e.g. adjunct displays) can or cannot help learning (Carney et al., 2002), but very little research exists about how people create their own presentations and how to assess their effectiveness in full representing the informational content (concept properties and relations). This cognitive problem concerns instructional designers but also learners that help themselves by constructing concept maps, diagrams or other kinds of displays by jointly employing texts and pictures.

The aim of the present work is to propose a new approach in considering representation of text and pictures, that takes into account the type of situation to be represented and its conceptual demands. The study was motivated by the idea that in order to be able to say how pictorial and symbolic elements interact, a common way to describe concepts expressed by both systems is needed.

In particular, the present study included the following steps:

(a) selecting some situations, that expressed some standard properties and relations
(b) studying how situation descriptions were empirically translated from a text format into pictures
(c) developing a representation system specifically designed for coping with pictorial meanings
(d) assessing the effectiveness of descriptions

The last step, assessing effectiveness, was only sketched in the present analysis, because - although the meaning of the expression "to assess effectiveness" of visual presentations seems clear enough (i.e. to express the same concepts, or gist, key ideas, as the verbal input) - in fact it may have different meanings. It may refer to different specific tasks (problem solving, communication, etc.) and different dependent measurements can be adopted (e.g. correct responses/reaction times in recognition or recall, number of problems solved, etc.). A specific study will be devoted to this subject, which deserves to be treated more thoroughly.

2. Method

Materials

Our study started with sentences that referred to situations of different kinds. We considered some situations that included interesting (from the pictorial/symbolic integration point of view) conceptual aspects or relations. This taxonomy is not meant to be exhaustive but was devised as a starting point. Sentences could describe mathematical or non-mathematical situations. There were spatial situations (relations such as "above", "nearby", etc.), set situations (where a set is divided into parts or subsets, like in arithmetic situations), and time situations (where events occur in different stages in time). Table 1 shows general characteristics of situations, with examples.

There were five cases: 1) no pictorial-symbolic integration was required (relations could be expressed only by pictorial elements); 2) use of numbers was implicitly required; 3) use of conventional symbols was implicitly required; 4) information could be expressed indifferently by pictorial or symbolic elements; 5) a double representation was required in order to account for transformations that implied a first-after sequence.

Descriptions did not concern problem solving situations, because preliminary trials had shown that a solution-oriented representation involves some disadvantages: participants would have been more anxious and would give more importance to solution strategies than to representation strategies.

Table 1 - General properties of situations

case 1 - Relationships expressible by pictorial elements
a) No relationships
b) Topological or ordinal spatial location
e.g.: above / between / adjacent

c) Metric spatial location
e.g.: near to…, far from…

case 2 - Properties expressible only by numbers
Non concretely countable objects
e.g.: one hundred houses

case 3 - Properties that require conventional symbols
a) Qualification
e.g.: is red / is green

b) Single belonging or possession
e.g.: Alan's

c) Multiple belonging or possession
e.g.: Alan & Burt's

case 4 - Mixed (can be expressed as pictures, symbols, or both)
a) Concretely countable objects
e.g.: two houses

b) Comparison, difference, correspondence
e.g.: more than / less than / how many

case 5 - Transformation
Reduction, addition (in this case there are two boxes, representing first-after times)
e.g.: Alan had …, then he gave … / , then he bought …

Table 2 (left column) shows sentences. Situations described by the sentences were arranged in increasing order of complexity and abstraction level.

Representations in the rightmost column in table 2 have been expressed using a predicate-argument notation. For example, the representation of sentence 14 means that, in order to fully express its meaning, one has to say that there is a first garden, possessed by Alan, which has a first set of trees (trees1), whose number is 50 (uncountable). One must also draw the inference that there is a second garden, belonging to Burt, which has a set of trees as well (trees2), and the sentence meaning to be conveyed is that the number of trees in the first set is greater than the number of trees in the second set. This sentence is particularly difficult to be expressed using only pictures, because of the presence of an uncountable quantity but also because an inference must be drawn and there is an unknown quantity (NUM-X). The distinction between countable and uncountable quantities has been based on commonsense assumptions (it is normally unlike to draw a picture for 100 houses); in some cases, when such assumption is not so clear (e.g. 8 books might or might not be drawn) it has not been specified.

Table 2 - Sentences and logical representation

Sentences*	Conceptual slots (objects, properties, and relations to be represented) in pred-arg notation
1. A house	OBJ(house)
2. Two houses	OBJ(house), NUM-C(2)
3. One hundred houses	OBJ(house), NUM-U(100)
4. Alan's house	OBJ(house), QUAL(POSS(A, house))
5. The house where Alan, Burt, and Charles live	OBJ(house), INF: QUAL(POSS((A,B,C),house))
6. The house on the mountain	OBJ(house), LOC-T(ON mountain)
7. Alan's house on the mountain	OBJ(house), LOC-T(ON mountain), QUAL(POSS(A))
8. Two houses on the mountain	OBJ(house), NUM-C(2), LOC-T(ON mountain)
9. One hundred houses on the mountain	OBJ(house), NUM-U(100),LOC-T(ON mountain)
10. A house with 100 windows	OBJ(house) OBJ(window), NUM-U(100)
11. A house has 50 windows at the 1st floor and 50 windows at the 2nd floor	OBJ(house) OBJ(window1), SET(floor(1), NUM-U(50)) OBJ(window2), SET(floor(2), NUM-U(50))
12. A house has 50 windows at the 1st floor and 50 windows at the 2nd floor. The 1st floor belongs to Alan; Burt and Charles live at the 2nd floor	OBJ(house) OBJ(window1),SET(floor(1),QUAL(POSS(A),NUM-U (50)) OBJ(window2,SET(floor(2),QUAL(POSS(B,C),NUM-U (50))
13. A house near the mountain	OBJ(house), LOC-M(NEAR mountain)
14. In Alan's garden there are 50 trees. Burt has more trees than Alan	SET(garden1, QUAL(POSS(A)), SET(trees1, NUM-U(50)) [INF: SET(garden2, QUAL(POSS(B), SET(trees2,NUM-X)] COMP (MORE-THAN, NUM-U(trees1), NUM-X(trees2))
15. Alan's house is in Park Street between the town council and the chemist	OBJ(house), QUAL(POSS(A), QUAL(NAME "Park Street", LOC-T(BETW t.c., chemist))
16. There are red books and green books	SET(books1, QUAL(COL red)) SET(books2, QUAL(COL green))
17. There are red books and green books. There are 34 red books and 85 books in all	SET(books1, QUAL(COL red, NUM-U(34))) SET(books2, QUAL(COL green, NUM-X) SET(all-books, NUM-U(85)))
18. Alan has 34 books. He read 12 of them, now has 22 books to read	SET(all-books, QUAL(POSS(A), NUM-U(34))) SET(read-books,QUAL(POSS(A), NUM(12)) SET(to-be-read-books, QUAL(POSS(A),NUM(22))
19. Burt had 15 books. He bought 8 more, now he has 23 books	TIME1, SET(prev-books, QUAL(POSS(B), NUM(15)) TIME2, SET(new-books, QUAL(POSS(B), NUM(8)) TIME3, SET(now-books, QUAL(POSS(B), NUM(23))

* Sentences have been adapted from Italian.

Legend

A, B, C	persons	NUM-U (N)	number-uncountable (number)
		NUM-X	number-unknown
COMP (relation, term1, term2)	comparison	OBJ	depictable object
INF (what)	inference	NUM (N)	number
LOC-M (relation, where)	location-metric	QUAL (q)	qualification
LOC-T (relation, where)	location-topological	SET (s)	set

NUM-C (N)	number-countable (number)	TIME	time sequence

kinds of qualification

COL (c)	color	POSS (who, what)	possession
NAME	name		

Participants

40 subjects participated in the experiment. All of them were volunteers, students at the University of Genoa.

Procedure

Participants were given a 19-page booklet; each page contained a verbal description of a situation printed on top of an empty box. Their task was “to represent without words” each situation. Drawings, single letters, numbers, and symbols were allowed; only a monochrome (black) pen was available. Subjects were also told that the representation should have been "clear enough in order that another person could reconstruct the sentence from the picture only". Sentences were presented in booklet pages in the same order as in table 2, by increasing complexity.

Results

Only 24 out of the original 40 booklets fully conformed to the requirements; the remaining 16 were discarded because either they were not completed or instructions were not consistently followed. A total of 456 (24 subjects X 19 situations) representations were thus obtained.

3. Descriptive analysis

a) Pictorial elements

Our aim at this stage was to devise a method for a descriptive analysis of how situation descriptions were empirically translated from a text format into pictures. In order to assess how situations were generally represented, the following pictorial elements were considered: type of picture, used symbols, operators, and connectors.

Type of picture

Type of picture	number	percentage
picture	403	88,4
diagram	13	2,8
picture & diagram (mixed)	8	1,8
set	4	0,9
no picture (only symbols)	28	6,1
TOTAL	456	100,0

The vast majority of representations were pictures. Diagrams were used only in a few cases for representing situations from 16 to 19. The set-theoretical notation (e.g. Wenn diagrams) was used very rarely.

In the vast majority of cases (92,8 %), pictorial representations were simple pictures. The remaining pictures can be analyzed more in detail, showing some interesting functions (strategies for expressing difficult aspects):

- *numeric correspondence* (1,2%), when subjects attempted to reach a numeric correspondence even in cases where the concept could have been expressed more easily by a number (e.g. 100 windows represented as a 10 by 10 matrix);
- *partial numeric correspondence* (0,9%), similar to the previous case, but where the numeric correspondence was partial and the completion was suggested by arithmetic operation (e.g. 50 windows represented as 5 windows with the symbol "x 10");
- *symbolic function* (1,9%) (e.g. a little square similar to a window picture, but used as a symbol associated with a number);
- *symbolic sequence* (1,6%) (similar to the previous case, but using a sequence: e.g. "a house with 100 windows" represented using a picture of a house, the number 100, and the picture of a window);
- *iconic* (1,6%) (e.g. a fire picture for representing the red color, a tree for green)

Symbols

Two kind of symbols were considered: numbers and letters. Numbers could have a cardinal or ordinal function, or they could act as simple labels. Letters generally had a label function, acting as captions for identifying something; in two cases they had the function of a legend, because the symbol was repeated outside the working area and associated with an explanation; in one case a string was used in a metonimic sense, when "Marx" was used inside a book picture in order to denote "red books".

Operators

Operators are special symbols that denote an operation to be performed. The operation could be intended in a wide sense as any action to be done upon a representation in order to transform it, or in a restricted sense as a mathematical operation. Examples of the first kind of operators are the symbol "x" to denotate "repeat this a number of times", or the symbols "…" to denotate "take more than this".

Types of operators	number	percentage
general	74	69,2
mathematical	33	30,8
TOTAL	107	100,0

Connectors

Connectors are symbols that link pictures or other symbols each other. *Arrows* were by far the most frequent kind of connectors. In the majority of cases (26), they indicated what a symbol referred to. In a few cases, arrows indicated where to put a symbol that did not fit into a picture, direction, development (e.g. from 1 window to 100 windows). In five cases, they had no recognisable function and were considered pleonastic.
Other connectors were *lines* and *enclosures* (no set-theoretical space partitions, with a function of conceptual focus or reinforcement: e.g. to circumscribe a part of the picture in order to highlight it or to put it in correspondence with a symbol)

Types of connectors				number	percentage
arrows				35	68,6
	arrow function	reference	26		

	indication	2		
	direction	1		
	developmen t	1		
	pleonastic	5		
enclosures			12	23,5
lines			3	5,9
other			1	2,0
TOTAL			51	100,0

b) Connection between pictorial elements and conceptual properties

In order to assess the quality of a pictorial sketch, the key condition to be checked is how well it is able to convey a complete information about situations. This means that a picture should represent objects and relevant properties so that they fit with original situations described by the original sentences. We considered how such properties were translated into pictorial data by using conceptual slots. To this aim, we developed a predicate-argument notational system specifically apt for coding elements with pictorial relevance. From our empirical data, for each conceptual slot (as already described in Table 2) we drew some actual iconic or symbolic representations. Some examples are described in Table 3 (for this analysis only 8 sets of pictures were selected).

For example, from Table 2 we see that a full translation into a sketch of the sentence 4 (Alan's house) has the following conceptual slots: OBJ(house), QUAL(POSS(A, house)), i.e., the concepts that must be expressed are that there is an object (a house), and that this object is qualified as being possessed by Alan (A).

From Table 3, we see that an object x [OBJ(x)] may be iconically expressed as PICT(x)or DIAPICT(x), i.e. a picture of x or a diagrammatic picture of x (replaced by "house" in this case).

Similarly, since the qualification of possession implies that there is an owner and something possessed [QUAL(POSS(owner, possession))], the owner may be iconically represented by a picture of a person [owner: PICT (person/owner)] or symbolically by a letter [owner: &LET] or a symbol on it [owner: &SYMB-ON(person)] and possession may be iconically represented as putting the owner spatially close to the thing possessed [possession: owner <close to> possession] or using an arrow to connect the two elements [possession: arrow (owner to possession)] .

Table 3 – Representations corresponding to conceptual slots

Conceptual slots	**Possible iconic representations**	**Possible symbolic representations**
OBJ(x)	PICT (x) DIAPICT(x)	
NUM-C (x)	ITER-PICT(x) ITER-DIAPICT(x) PERSP	&NUM(x)

NUM-U (x)	ITER-PICT(x) ITER-DIAPICT(x) TIMES(x) DOTS	&NUM(x) OPER(&"x")
QUAL (POSS(owner,possession))	owner: PICT (person/owner) possession: owner <close to> possession possession: arrow (owner to possession)	owner: &LET owner: &SYMB-ON (person)
QUAL (COL (color))	color: <texture>	color: &LET
QUAL (NAME (name))		name: &LET
LOC-T (ON x,y) LOC-T (BETW x,y)	PICT <ON> x,y PICT <between> x,y	
SET (x)	SET-DEL: • DIAPICT(x) • ITER-PICT (x) • ENCLOSURE • SPACEPART	
TIMEx	OPER (arrow) <close to>	

LEGEND:

symbolic elements are preceded by &
PICT= picture (rich)
DIAPICT = diagrammatic picture (only simplified shape)
NUM = number
LET=letter
OPER=operator
ITER-PICT = iterated identical pictures (/C corresponding, /NC non corresponding number)
ITER-DIAPICT = iterated diagrammatic pictures (/C corresponding, /NC non corresponding number)
PERSP = use of perspective for an indefinite quantity (e.g. houses smaller and smaller)
SET-DEL = set delimiter
ENCLOSURE = closed line (circle or other polygon): Venn diagrams are a particular case
SPACEPART = space partition (the whole space is divided into different regions by using a line or other means, e.g. a fence)
IRR (x) = irrelevant objects (e.g. a tree when only a house should have been represented)
ERR = erratic (very particular representations, like an apartment map for a house)
<in brackets> = implicit spatial relations or graphical artifacts

conventional operators
TIMES (X) = repeat this
GRTHAN/LESSTHAN (>, <)

Table 4 – Actual representation of sentences in our data

Sentences	Conceptual slots	Representation	N
1. A house	OBJ(house)	PICT(house) PICT(house), IRR(x) DIAPICT(house)	4 2 2

2. Two houses	OBJ(house), NUM-C(2)	PICT (house), ITER-PICT(house) DIAPICT(house), ITER-DIAPICT(house) PICT (house), IRR(x), ITER-PICT(house)	5 2 1
3. One hundred houses	OBJ(house), NUM-U(100)	DIAPICT(house), ITER-DIAPICT(house) PICT (house), OPER(&“x”), &NUM(100) DIAPICT(house), ITER-DIAPICT(house), DOTS PICT (house), &NUM(100) PICT (house), &NUM(100), DOTS DIAPICT(house), &NUM(100) PICT(house), ITER-PICT(house),PERSP, DOTS	2 1 1 1 1 1 1
4. Alan's house	OBJ(house), QUAL(POSS(A, house))	PICT(house), PICT(person),&SYMB-ON(person) PICT(house), PICT(person),&SYMB-ON(house) PICT(house), PICT(person), <CLOSE>(person,house) PICT(house), PICT(person), IRR(x) PICT(house), PICT(person), ARROW(person to house) DIAPICT(house), &LET(A) ERR	1 1 1 1 1 1 2
5. The house where Alan, Burt, and Charles live	OBJ(house), INF: QUAL(POSS((A,B,C),house))	PICT(house), ITER-PICT(person),&LET, IRR(x) PICT(house), ITER-PICT(person), ARROW(person to house) PICT(house), ITER-PICT(person) DIAPICT(house), &LET(A,B,C) PICT(house), PICT(person),&SYMB-ON(person) PICT(house), &SYMB-ON(house) ERR	1 1 1 1 1 1 2
6. The house on the mountain	OBJ(house), LOC-T(ON mountain)	PICT(house),PICT <on> house,mountain PICT(house),PICT <on> house,mountain, IRR(x)	5 3
7. Alan's house on the mountain	OBJ(house), LOC-T(ON mountain), QUAL(POSS(A))	PICT(house),PICT <on> house,mountain, PICT(person) PICT(house),PICT <on> house,mountain, PICT(person), ARROW(person to house) PICT(house), PICT <on> house,mountain,PICT(person),&LET(A) PICT(house), PICT <on> house,mountain,PICT(person), <CLOSE>(person,house) PICT(house),PICT <on> house,mountain, IRR(x) PICT(house),PICT <on> house,mountain PICT(house),PICT <on> house,mountain, IRR(x)	1 1 1 2 1 1 1

Stage 2

Method

As explained in the introduction, the step concerning the assessment of picture effectiveness was only sketched in the present study, since effectiveness is not only a matter of communication and could be measured in different ways. Here we operationally defined it as making other people able to understand what situation one picture is referring to.

In the second stage, other participants acted as judges; their task was to match pictures drawn by the subjects in stage 1 (in random order) with the sentences from Table 2. The aim of this procedure was to evaluate the appropriateness of the pictures to their intended purpose, i.e. communicating information to other people. Participants in stage 2 were not taught explicit procedures, in order to encourage them to develop their own implicit procedures as they encountered more and more complex and abstract situations.

Participants

8 subjects, students at the University of Genoa, participated in the experiment as volunteers.

Materials and procedure

8 sets of sketches produced by 8 participants in stage 1 were randomly selected for this stage. Each set was composed of all 19 pictures, so that in each set all 19 sentences had been depicted and there was one correct picture-sentence match. Each new subject here acted as a “judge”. Their task was to match each picture with the corresponding sentence. Pictures were presented in random order. Sentences were listed in alphabetical order and, in order to avoid that numbers acted as a possible cue for correct picture-sentence matching, all numbers were replaced by x,y,z,.. letters. For example, sentence number 11 became: “A house has x windows at the y-th floor and z windows at the t-th floor”.

Results and discussion

Table 5 shows the percentage of correct matchings picture-sentence out of the 152 total available sketches. Nine sketches were never recognized. Seven of them (corresponding in two cases to sentence 7, in two cases to sentence 12, and in other cases to sentences 3, 5, 11) did not have the features needed for representing corresponding sentences.

Table 5 - Scores from the most difficult to the easiest sentence

sentence	Sum	Mean	Mean st.dev.
17. There are red books and green books. There are 34 red books and 85 books in all	**25**	**0,39**	**0,49**
11. A house has 50 windows at the 1st floor and 50 windows at the 2nd floor	**28**	**0,44**	**0,34**
12. A house has 50 windows at the 1st floor and 50 windows at the 2nd floor. The 1st floor belongs to Alan; Burt and Charles live at the 2nd floor	**31**	**0,48**	**0,38**
7. Alan's house on the mountain	**33**	**0,52**	**0,36**
18. Alan has 34 books. He read 12 of them, now has 22 books to read	**34**	**0,53**	**0,32**
4. Alan's house	**41**	**0,64**	**0,39**
19. Burt had 15 books. He bought 8 more, now he has 23 books	**41**	**0,64**	**0,40**
5. The house where Alan, Burt, and Charles live	**42**	**0,66**	**0,24**
10. A house with 100 windows	**44**	**0,69**	**0,42**
3. One hundred houses	**46**	**0,72**	**0,23**
8. Two houses on the mountain	**46**	**0,72**	**0,31**
9. One hundred houses on the mountain	**47**	**0,73**	**0,40**
6. The house on the mountain	**47**	**0,73**	**0,44**
1. A house	**53**	**0,83**	**0,36**
15. Alan's house is in Park Street between the town council and the chemist	**54**	**0,84**	**0,22**
16. There are red books and green books	**55**	**0,86**	**0,27**
2. Two houses	**61**	**0,95**	**0,13**
13. A house near the mountain	**61**	**0,95**	**0,13**
14. In Alan's garden there are 50 trees. Burt has more trees than Alan	**62**	**0,97**	**0,09**

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Appendix: Some picture examples
(printed numbers added for coding purposes)