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Modelling the stages of the identity theory of object-concept development in infancy

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Abstract. A computational model is presented for the three stages of development of the object concept in infancy identified by Bower and Wishart in their research. The stages are described by sets of PROLOG clauses that interpret object structures representing the perceptual phenomena interpreted by the infants themselves. The infant's changes between developmental stages can be described by differences between the rules modelling each stage. Three experiments are presented and the behaviour of the PROLOG model is described for each stage of development. Motion, rest, and boundedness of objects constitute the theoretical underpinning of the running PROLOG model and are hypothesized as the invariant aspects of perception that explain the behaviour of the infant at each stage of development. A possible explanation for transitions between stages is offered and justified in part by the output of the model, which in turn is used to predict the behavioural outcome of an experiment.

1 Introduction: the aims of the study

The task of this paper is to present a computational model for a particular theory of the development of the object concept by infants: the identity theory proposed by T G R Bower and his associates (for detailed references, see section 2). A first attempt at computer simulation of this period of cognitive development has already been published in this journal (Luger et al 1983a). This first paper dealt only with the first two of the three hypothesised stages of development, comparing the output of the computer model with data collected in five studies by Bower and co-workers of infants' responses to simple movement events involving a single unoccluded object.

The present paper expands on the earlier paper in three ways. It extends one of the experiments modelled in the first paper to its logical conclusion, simulating behaviour at all three levels of development. In doing so, it succeeds in modelling an experiment believed in one previous modelling attempt (Prazdny 1980) to be unmodellable. It also attempts to model two further and more complex object-concept studies, both of which involve partial or total occlusion of a moving object. In one case, the behaviour of infants in all three stages was already known (Wishart 1979; Bower 1982); in the other, the data, although collected, had not yet been analysed (Bower 1983). The usefulness of this modelling attempt will therefore be tested at two levels: on its ability to simulate all three stages of infant object-concept development, and on its ability to predict that behaviour (see section 4.3).

Third—and probably in the long term most importantly—this paper will take a preliminary look at the possibility of modelling not only the stages of development but also the transition processes between these stages. This will be done in terms of a cost-gain analysis in which it is assumed that, for development to occur, the cost of increasing the perceptual analysis must be outweighed by the conceptual gain resulting from altering the existing identity rule to a new and higher level (Bower, 1982).

The rules or procedures within the model presented here are intended to offer a degree of explanation for the mechanisms by which the infant produces particular behaviours at each stage of development. It is hoped that the development itself can be elucidated by analysis of the rule shifts between stages of the model (see section 5). The computer is being used to describe and implement a model or a theory of development. The use of the computer model in this instance is much the same as the physicist's use of mathematics to model phenomena in statistical mechanics: it lends consistency, controllability, and verifiability, all necessary elements for any empirical study. Johnson-Laird (1981) describes the advantages that a program can bring to a theorist:

> "First, a program concentrates the mind marvellously. Second, a program transforms mysticism into information processing, forcing the theorist to make explicit and translate vague terminology into concrete proposals. Third, a program provides a secure test of consistency of the theory, thereby allowing complicated interactive components to be safely assembled. Fourth, a program provides a working model that is dynamic, not static, and that can be tested directly against human performance".

This fourth advantage of a program model of performance is by no means the least important. The running program gives the opportunity of a dynamic validation of the theory under scrutiny by providing the possibility of simulating experiments. If a researcher wants to see what results might be expected from the theory in a new experiment, it can be set up and run on the computer. Careful analysis of the results of any such simulation and comparison with subsequently obtained empirical results then allows for the continual 'fine tuning' of the model.

Critics of simulation attempts frequently accuse the models offered of irrefutability—using some variation on the old 'garbage-in-garbage-out' argument. There are, however, two clear ways to evaluate a computer model such as the one proposed. The first, since it is based on a particular theory of object-concept development, the identity theory, would be to find empirical results that that theory cannot properly explain. The history of science suggests that this will inevitably happen. In the meantime, the model allows the comfort of consistency within one particular explanatory framework. The second way the model may be refuted is if it is not sufficiently flexible to describe new developmental data which is consistent within the identity paradigm, that is, if fine tuning of the model (section 4) still results in a failure to match the computer output with the new empirical results. In this case the model would have to be redesigned in the light of the new evidence. To date, our own model has survived both of these tests.

The background of psychological studies with infants that has led to the identity theory of object-concept development will now be presented. Our PROLOG model of this period of development will then follow.

2 The identity theory of object-concept development

It is now nearly fifty years since Piaget first noted that the infant's understanding—or, more correctly, misunderstanding—of objects passes through an apparently invariant sequence of six stages (Piaget 1936, 1937, 1946). Today, despite the many criticisms of the inadequacy of his observational techniques and the use of only his three children as subjects, Piaget's descriptions of these six stages and their associated behaviours still remain essentially intact, having been confirmed to be both accurate and cross-culturally valid (Gouin-Décarie 1965; Casati and Lézine 1968; Boyle 1969; Corman and Escalona 1969; Dasen 1973; Kramer et al 1975; Uzgiris and Hunt 1975; Wishart and Bower 1984a). Recent years, in fact, have seen a dramatic revival in attention to this area of development, with the object concept becoming one of the most researched topics in infant psychology (for reviews see Elkind and Sameroff 1970; Gratch 1975; Harris 1975, 1984; Schuberth 1982). One reason for this is that rate of object-concept development seems to be the only change in infancy that predicts later rates of change in cognitive functioning (Wachs 1975).

Few of today's researchers would disagree that infants everywhere and of every level of intelligence will at some point pass through each of the six stages identified by Piaget. There is, however, considerable disagreement and speculation as to what produces the characteristic errors of each stage and what exactly in cognitive terms these stages represent. Much of the recent work on infant search behaviour has produced evidence of further object misunderstandings which cannot be fitted into Piaget's original theory of object-concept development (for reviews see Wishart 1979; Bower 1982) and alternative accounts have been suggested by a number of other researchers (for example, Butterworth 1975; Cornell 1978; Sophian and Wellman 1980).

This paper represents an attempt to simulate this period of development which is based on one of these alternative accounts: Bower's identity theory of object-concept development. Reasons for favouring this account over others will not be presented in detail here, but are given in Wishart (1979) and Wishart and Bower (1984a). The identity theory of object-concept development is firmly grounded in experimental findings (see below) and is one of the few theories which is capable of accounting for the behaviours seen at all of the stages in classic object-permanence testing. Unlike many of its competitors, it can also account for many of the other bizarre behaviours produced by young infants in response to objects and events involving objects (see, for example, Neilson 1982; Wishart and Bower 1984a).

The identity theory suggests that the conceptual problem which underlies the six stages of object-concept behaviour is one of object identity rather than object permanence. According to this theory, the infant's main problem in understanding the nature of objects lies not in discovering their independent existence, but rather in understanding the spatiotemporal relationships which underlie their identity.

In identity theory a basic idea of object reality (including some idea of permanence) is assumed to be present very early in the sensori-motor period (Bower 1967). The infant is seen rather as having difficulty in maintaining the identity of an object throughout the spatiotemporal transformations which occur when an object participates in an event sequence. This difficulty is present regardless of whether the event entails temporary disappearance of the object or not (Bower and Wishart 1973; Butterworth 1977; Neilson 1982) and is particularly acute if the sequence involves close interaction with any other object (Bresson et al 1977; Lucas and Uzgiris 1977; de Schonen and Bower 1978; Wishart 1979; Spelke 1983).

In this theory, development is seen as a progressive refinement of the infant's rules for attributing identity to an object over time. The infant moves from the simple recognition that an object is the same object at different times and in different places, through to more elaborate notions which define identity in a much stricter sense, with the object not only being recognised as featurally the same but as identical in the sense of being one and the same object when involved in any event sequence, that is, the same *and only* such object involved.

The identity hypothesis accepts the six behavioural stages observed by Piaget as veridical, and forwards a sequence of five behavioural search rules which could account for the behaviour of each of these six stages. Underlying these five search rules, however, is assumed to be a sequence of only three conceptual rules, the rules which define identity and in part determine the search rules.

Each change in level means that the infant can maintain the identity of an object over increasingly complex event sequences. Each new identity rule reduces the population of 'objects' with which the infant must deal and therefore represents a considerable cognitive achievement.

These rules and the psychological evidence for their validity are outlined below (for a fuller account, see Wishart 1979).

Rule 1 (Piaget's stages I and II)
An object is a bounded volume of space in a particular place or on a particular path of movement.

It immediately follows from this rule that, at any given time, two objects cannot be in the same place and that two objects cannot be on the same path of movement. For the infant at this stage of development, an object is defined either as a bounded volume of space in a certain place or as a bounded volume of space on a certain path of movement. A violation of rule 1, such as replacement of a stationary object by a totally different object, will be treated by this level of infant as a transformation of the original object rather than as a replacement by another object (Bower 1974).

Application of this rule in search tasks would lead to the following search behaviours:

to find a stationary object, look for it in the place where it usually is.

[If the previously stationary object has in fact started to move, the subject at this level of object-concept development typically looks back to the place the object formerly occupied, making what has become known as a place error (Bower et al 1971)].

to locate a moving object, look for it along its path of movement.

[Even if in fact the object has now stopped, this level of infant frequently continues to follow its former path of movement, making what is known as a movement error (Bower and Paterson, 1973)].

Rule 2 (Piaget's stages III–V)
An object is a bounded volume of space of a certain size, shape, and colour which can move from place to place along trajectories.

Now place and movement errors no longer occur because they are mediated by the perceptual features of the object, which were ignored in the application of rule 1.

It is still true that two objects cannot be in the same place or on the same path of movement at the same time, that is, that the bounded volume of space that defines the object cannot be violated. Thus total or partial occlusion of the object will still cause problems for the infant operating with rule 2.

Search behaviour for this level of infant will include finding an object by searching for it in its usual place, or if it has moved, along its path of movement. Since featural information is incorporated in this rule for identifying an object, any event sequence violating the perceptual integrity of the object (as when the object is covered by a cup or any other occluder) will be treated by the infant as the replacement rather than transformation of the original object by another object. Thus behaviour in this situation will be:

to find an object that has mysteriously disappeared, remove the object that has replaced it.

which with experience, will be modified to:

to find the disappearing object, remove the object which is in the place where the desired object was last seen.

This will allow the infant to 'succeed' in Piaget's stage III–IV and IV–V tasks but does not represent any true understanding of the spatial interactions between object and occluder.

Rule 3 (Piaget's stage VI)
Two or more objects cannot be in the same place or on the same path of movement simultaneously *unless* they bear a spatial relationship to each other which involves the sharing of common boundaries.

Here the identity rule is essentially the same as in rule 2 but is modified to fit with the infant's experiences of the consequences of interactions between objects.

For an infant working with only rule 1, an object which moves then stops or which enters into a spatial relationship with another object in such a way as to lose or mask its identifying boundaries will have disappeared mysteriously. With rule 2, only the latter kind of event will cause identity confusion and erroneous search behaviour. Not until acquisition of rule 3 can the infant understand that a spatial relationship between two objects does not violate the identity of either. Before reaching this understanding, he/she may succeed eventually in solving problems involving spatial relationships between two or more objects. These successful search strategies are, however, highly specific to particular problem situations and do not lead to success in other conceptually similar tasks (Wishart 1979).

In summary, then, Bower and Wishart hypothesize that the infant develops a progressively more comprehensive set of rules for recognising and maintaining the identity of an object over time. The staged acquisition of these rules both directs the infant's attempts to relocate objects and explains the erroneous behaviour seen on the traditional object-permanence tasks. As one rule is replaced by the next, the infant comes closer to appreciation of the independent properties of individual objects. At maturity these rules will be sufficiently developed to allow an object to interact in common space with any other object in virtually any event sequence without risk to its unique identity.

It should be noted that this theory (and its computer model) only applies to the domain of study listed as development of the object concept. Many legitimate problems for research are assumed, for this purpose, to be solved. For example, there is no interest in *how* the baby perceives movement; it is known that the infant *can* perceive movement. Movement perception, while itself fascinating (Harris et al 1974), is in terms of this model an unanalysed primitive. The same is true of detection of an object against a background, what used to be called the figure-ground problem. Infants do this in experiments; for the purposes of this model, how they do it is irrelevant. Lastly, while it is clear that infants can discriminate between different solid forms (Fantz 1961; Day and McKenzie 1973) there is evidence that they do not use these discriminative abilities for identification at the beginning of this segment of development. Our primitive object has therefore no attributed form but is merely a bounded volume. Nothing more than that is needed to account for the behaviours seen. While, with development, there are changes in behaviour in the tasks used, even adults under some circumstances ignore form and identify objects on the basis of place and movement (Michotte 1962; Michotte et al 1964).

The identity theory differs from other theories of object-concept development in that it is based on a differentiation theory rather than a constructionist theory. Development does not produce an eventual large scale notion of object permanence. Rather the child develops progressively more and more refined rules about which object transformations leave the object as a continuing identity and which do not. The starting point for most other theories is the statement that "out of sight is out of mind for the young infant". A corollary of that statement is that with development the child constructs a rule which says "out of sight is not out of mind". Both statements are wrong. Invisibility is neither necessary for out-of-mind behaviour (Bower 1967; Butterworth 1977; Bresson et al 1977; Wishart and Bower 1984a;

Neilson 1982) nor sufficient (Bower and Wishart 1973) in even the youngest infants studied. Even adults will show out-of-mind behaviour as a consequence of some of the transformations that perturb babies (Michotte 1962). It would be maladaptive if they did not, doomed forever to eating their cake and wondering why they no longer have it. The identity theory is at least congruent with all extant data. It is heterodox in that it does not assume that the infant is a *tabula rasa* at birth. Since, however, no one has demonstrated this—and would offend the canons of scientific methods were they to try, in that one cannot assert a null hypothesis—this does not seem a great weakness.

A PROLOG model of the three rules described above will be given in the next section along with the results of several experiments showing the model interpreting different perceptual situations.

3 The PROLOG model of the three stages of development

3.1 *The model*

The computational description of object identity theory is written in PROLOG, a very high-level computer language. PROLOG was designed in an attempt to use first-order predicate logic as a programming language. Although PROLOG is not pure logic programming (Kowalski 1979) its declarative/procedural inferencing does offer a powerful tool for modelling human problem solving (Luger 1981). More detailed descriptions of PROLOG may be found elsewhere (Warren and Periera 1977; Clocksin and Mellish 1981).

The model makes two different uses of PROLOG clauses: first, declarations or facts; second, procedures or inference rules. The declarations or facts are used to build the object structures that make up the experiments. For instance,

location(obj*n*, *x*, *y*, *z*, *t*)
colour(obj*n*, red, *t*)
size(obj*n*, 4, *t*)
shape(obj*n*, sphere, *t*)

indicate that "the location of a structure called obj*n* is at point (*x*, *y*, *z*) at time *t*; obj*n* is a red sphere having radius 4 at time *t*".

The second use of PROLOG code is as procedures or rules. A rule is stated in the form "A ⊢ B, C, D" which may be interpreted procedurally as "to verify that A is true, try to perform B, C, and D". B, C, and D may be facts as described above or may themselves be rules each requiring other facts or rules to be true for their ultimate verification. The fact that the search technique in PROLOG is a left-to-right depth-first attempt at verification is an artifact of the interpreter and not meant to limit the model. In fact, the set of PROLOG rules used to describe each stage of development is intended to model the set of competencies that any infant may or may not have.

As will be seen below, the model is not based on records on specific S-R behaviours (for example, eyes move left—stop—return 40°), but rather on higher-level descriptions of these. The term 'level' is used here in the sense used by Russell (1910) and introduced to psychology by Bateson (1972). It should be clear that the rules begin in the mind of the adult experimenter; the adult experimenter is, however, trying to infer the rules that operate in the mind of the baby. If the two match up, the result would be a complete theory of at least one segment of development. The computer model is important in that a computer, unlike one's fellow scientists, will not be confused by an ambiguous sentence. To try then to make a computer act like a baby, one must be very clear about the rules one is trying to attribute to the baby. The term 'rules' is very important: in development most psychologists would admit that the same rules or concepts can be indexed by different behaviours, eye movements, hand movements, or even mouth movements in the case of the object concept (Gouin-Décarie 1969). A computer has neither eyes, hands, nor mouth, but this is irrelevant. The model is intended to simulate rules and rule changes, without reference to specific physiological or behavioural details.

This is important in evaluating the program in which a 'snapshot' model of perception (Neisser 1976) and serial processing of data (see below) is employed. Neither of these need be true of the real infant; in fact there are arguments that can be made for and against each position (Gibson 1969; Rosch 1977). What is important is the output of the human information processing system. For present purposes the *nature* of this system is as irrelevant as the precise details of the associated biochemical processes. Until there are further data available on the human system for symbol manipulation that indicate that these descriptions are incorrect—and as yet no such data exist—we will proceed with the analysis. The emphasis is not on the *particulars* of behaviour, but on the rules or concepts that generate such behaviour. (For further discussion on these points see Luger et al 1983a).

A description of the PROLOG rules modelling each stage of development is now given. Rather than give PROLOG code we list the competencies, expectations, and so on, that make up the rules for each stage of development.

3.2 *The* PROLOG *rules for the three stages*

Stage 1

(i) Focus on a location. This location has been 'constructed' from the locations of the immediately preceding object structures found [see (v) below].

(ii) Find an object within a fixed distance of where focused. If an object cannot be found report failure and look back to the preceding object found (the previous 'snapshot').

(iii) Check the object for interest, seeing if it has volume or mass. This is done by considering two slightly different views of the object.

(iv) Check if all boundaries are intact. This is done by checking continuity of boundedness across snapshots.

(v) Based on the object at snapshot n and snapshot $n-1$, construct an appropriate expected location for snapshot $n+1$.

Stage 2

The competencies and expectations of stage 2 are almost identical to those of stage 1, as one might expect, except that a check occurs between (iii) and (iv) above, where further perceptual relationships (size, colour, shape) are compared between the object at snapshot $n-1$ and the object found at snapshot n.

Stage 3

The competencies of stage 3 include all those at stage 1 and in addition consult the new perceptual check of stage 2 not only as in stage 2, between (iii) and (iv), but again after the boundaries are scrutinised, after (iv) above.

Experiments are run by the program in two independent steps: the *creation* of the object structures that represent the physical experimental situation; then, the *parsing* of this set of snapshots or object structures by the rules of a particular developmental stage.

To demonstrate these steps the appendix to this paper describes in some detail the snapshots and analysis in the particular case of experiment 2 (see below)(1). The two steps, creation and parsing, provide for (in fact, have an a priori commitment to) an

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(1) Space limitations preclude reproduction of the full working program here. A full copy can, however, be obtained by those interested on writing to the senior author at the Department of Computer Science, University of New Mexico, Albuquerque, NM 87131, USA.

independence of the object structure and its perception. This means that there is no interaction between the percept of an object and the cognizing subject that in any way changes the nature of the percept. The changes come in the subject's interpretation of that percept. This commitment to the primacy of perception allows description of its origins and presence according to a number of differing theories (Marr 1978; Ullman 1978). This particular program does not parse retinal arrays to detect edges or perform figure-ground separation. (However, it does detect boundary violations such as partial occlusion, see experiments 2 and 3 below). Moreover, the perception of motion and changes of motion by calculating differences in positions over time is an irrelevant implementation detail; that is, like the feature detection which characterises stage 2, how this is actually accomplished by the infant is an empirical question to be answered by researchers considering these aspects of human response.

In summary then, it is hypothesized that the symbolic output of the detection mechanisms for feature and motion is available to the cognizing subject. We emphasize the descriptive adequacy of the internal symbol structure and the interpretative adequacy of the subject's manipulation of such symbol structures. Furthermore, the changes in the computational rules expressing the interpretative adequacy of infants at various stages of development are hypothesized to offer explanation of that development.

4 The three experiments

Each experiment of this study was chosen for a reason. Experiment 1 models object-concept data that Prazdny (1980) could not describe with his model. Experiment 2 also models a study already run with human infants. In this case, data are available not only on behaviour at each stage of development but also on the effect of regular exposure to this tracking task on the process of development itself (Wishart 1979; Bower 1982). Experiment 3 was originally done as a simulation of a study not yet run with infants. Preliminary results of the infant study are now available (Bower 1983) and will be compared with the results of the program.

All three stages of development are now described for each modelling experiment. A description of the snapshots for each experiment may be found in figures 1-3.

4.1 *Experiment 1*

In a computational model of the object concept in infants presented in this journal, Prazdny (1980) described several experiments his model could perform but then described a particular set of experimental data it could not account for. An earlier paper by the present authors (Luger et al 1983a) described an alternative model for this period in development which could also model the experiments Prazdny succeeded in modelling, but could in addition succeed in modelling the early stages of the experimental data on which Prazdny's program failed. While every program has its limiting conditions of application, Prazdny's failure to model this particular set of empirical results seemed to us to be due to a failure to appreciate that the infant's tracking behaviour is directed by conceptual output rather than perceptual input (see Luger et al 1983a). Experiment 1 of this paper succeeds in modelling all three stages of the experimental data on which Prazdny's program failed.

In experiment 1, a yellow sphere of radius 2 is located at (60, 4, 10) at time 1 (see figure 1); (60, 4, 10) marks the (*x*—left-right, *y*—up-down, *z*—depth) coordinates of a three-dimensional cartesian space. It remains stationary for three time periods, or snapshots, and then moves to the right with respect to the infant, who views it from the point (60, 0, 0). After moving for three time periods, the sphere arrives at (72, 4, 10) where it again rests for three time periods before it moves left and back to its starting point (60, 4, 10). This same sequence of rest and motion is repeated three more times. Then, instead of moving off to the right as usual, it moves to the left for three time periods, coming to rest at location (48, 4, 10). Here the experiment ends.

The results of applying the computer model in experiment 1 may be summarised as follows: The PROLOG model for stage 1 produces movement and place errors

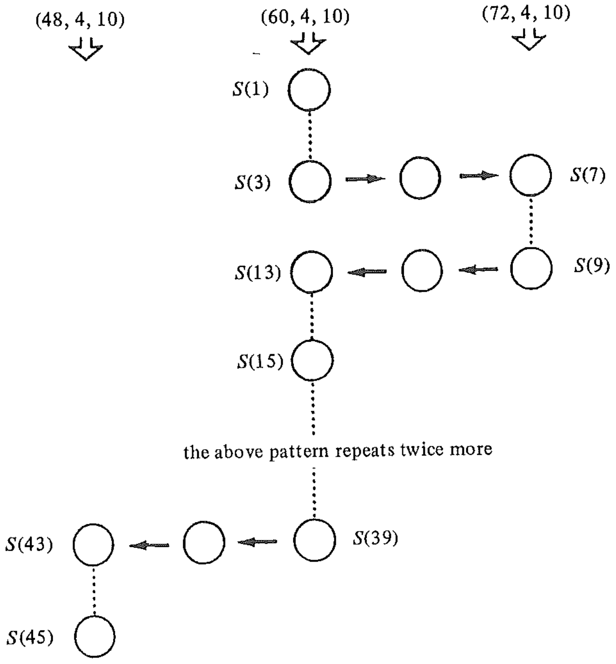

Figure 1. The snapshots of experiment 1, where $S(t)$ indicates the snapshot at time t and (x, y, z) indicates the centre of the object in a cartesian 3-dimensional space. The object is a yellow sphere of radius 2. The infant is located at (60, 0, 0).

Table 1. The results across all stages of experiment 1.

Object number	Time	Reason
Stage 1		
1	1-3	object at rest
2	4-6	object in motion
3	7-9	object at rest
4	10-12	object in motion
5 (same as 1)	13-15	object at rest
6 (same as 2)	16-18	object in motion
7 (same as 3)	19-21	object at rest
8 (same as 4)	22-24	object in motion
9 (same as 1)	25-27	object at rest
10 (same as 2)	28-30	object in motion
11 (same as 3)	31-33	object at rest
12 (same as 4)	34-36	object in motion
13 (same as 1)	37-39	object at rest
14	40-42	object in motion
15	43-45	object at rest
Stage 2		
1	1-45	object in rest/motion
Stage 3		
1	1-45	object in rest/motion

each time the object either started in motion or stopped, fifteen objects in all (table 1). There was no problem following the new motion in a different direction as long as the object's locations were close enough to each other across consecutive time intervals. ('Close enough' is an empirically testable measure.) Stage 2 infants only saw one object since their perceptual checks were able to determine two objects as one and the same if colour and size measures remained constant across time. Because there were no border violations stage 3 gave the same results as stage 2. The computer model assumes only a one snapshot memory of place or movement. A more sophisticated memory, one in which the number of 'objects' in table 1 would be reduced, is under consideration (see section 4.3).

These results fit well with the actual behaviours produced by infants at each stage of development in response to this tracking task (Bower and Paterson 1973).

4.2 *Experiment 2*

Experiment 2 models data already collected in work with infants at the Department of Psychology of the University of Edinburgh (Wishart 1979; Bower 1982). The original study was formulated to test whether with repeated exposure to motion, rest and partial occlusion of objects, infants could be accelerated through the stages of development of the object concept. A further aim was to determine whether any acceleration in development found would transfer to other conceptually related tasks (see section 5).

Experiment 2 (figure 2) has two objects, a green cube and an occluder, which the infant views from position (36, 0, 0). The occluder, in this case a black platform of length 8, height 6 and depth 6, remains centred at location (36, 4, 6) for all time periods. The green cube of length 4, height 4, and depth 4 remains at location (4, 8, 10) for the first five time periods. From times 6 to 20 it moves right with respect to the infant until it rests, again for five time periods, at location (68, 8, 10). While passing to the right the bottom boundary of the cube is obscured by the platform from times 11 to 15. This occlusion is worked out from perspective lines for the two objects with respect to the fixed location of the infant. After resting on the right (68, 8, 10) the object retraces the path back to the original starting place

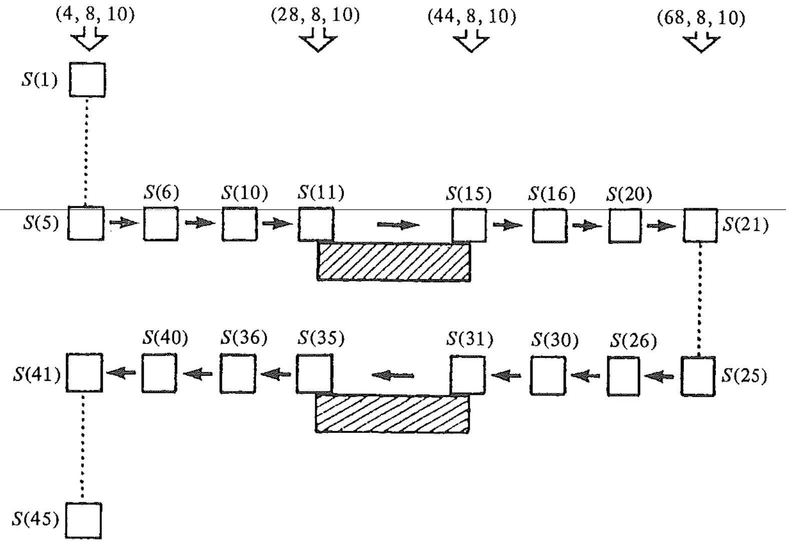

Figure 2. The snapshots of experiment 2. The object (moving and at rest) is a green cube of size 2. The occluder is black and size 4. The infant is located at (36, 0, 0).

(4, 8, 10), repeating the partial occlusion in the middle of the path, from times 31 to 35. After resting on the left, again for five time periods, experiment 2 ends. (For a fuller description, see the appendix.)

It may seem strange to refer to the platform in experiment 2 as an occluder since a platform is not conventionally thought to be an occluder. However infants produce the same sequence of behaviours with platforms as they do with more traditional occluders such as screens or tunnels (Piaget 1936; Bresson et al 1977; Wishart 1979). The model, like the baby, treats these three occluders as equivalent.

In experiment 2, the model at stage 1 found a new object when either motion or rest or boundedness was violated (9 in all). Stage 2, using perceptual checks, found new objects only when boundedness was violated (5 objects). Stage 3 found only one object, since perceptual checks of size and colour consistency were able to override violations of rest, motion and boundedness. Table 2 summarizes the number of objects found at each stage of development and the justification given by the program for each new object found. Again, these results are in line with empirical findings reported in the literature (Wishart 1979; Bower 1982).

Table 2. The results across all stages of experiment 2.

Object number	Time	Reason
Stage 1		
1	1-5	object at rest
2	6-10	object in motion
3	11-15	boundary violation (object plus occluder)
4	16-20	end violation/object in motion
5	21-25	object at rest
6	26-30	object in motion
7 (same as 3)	31-35	boundary violation (object plus occluder)
8	36-40	end violation/object in motion
9 (same as 1)	41-45	object at rest
Stage 2		
1	1-10	object at rest
2	11-15	boundary violation (object plus occluder)
3	16-30	end violation
4 (same as 2)	31-35	boundary violation (object plus occluder)
5 (same as 1)	36-45	end violation
Stage 3		
1	1-45	object at rest/in motion

4.3 *Experiment 3*

Unlike experiments 1 and 2, experiment 3 simulated a tracking task for which empirical data were not yet available. During the analysis of the empirical results of experiment 2, the possibility of describing changes between developmental stages in terms of a cost/gain metric emerged (Bower 1982). Experiment 3 was run by the computer as part of the testing of new hypotheses within this cost/gain metric. A longitudinal study with infants was subsequently carried out (Bower, 1983; Wishart and Bower 1984b).

Experiment 3 (figure 3) is much like experiment 2 except that eight different objects are used. The occluder again remains in a constant position throughout the experiment, at location (36, 4, 6). In the particular case modelled here, the occluder is a grey rectangular platform of length 8 and height and depth 6. A large green star in the location (4, 8, 10) begins the experiment and remains fixed there for five time periods. At time 6, the star changes to an orange and yellow sphere and moves right for the next five time periods. At time 11 and at location (28, 8, 10) the sphere changes to a small pink rectangle whose bottom boundary is obscured by the occluder. After five time periods, at time 16 and location (48, 8, 10), the pink rectangle ends its partial occlusion and changes to a large green and yellow triangle and continues its motion to the right. At time 21, the triangle changes to a small orange ellipse and stays in the fixed location (68, 8, 10) for 5 time periods. At time 26, the ellipse changes to a large yellow and green hexagon and begins its motion back to the left. At time 31 the hexagon changes back to the small pink rectangle and again goes into occlusion. At time 36 the small rectangle changes to a large unoccluded yellow and orange cube. Finally, at time 41 the cube changes to the original large green star, remaining stationary at location (4, 8, 10). After five time periods the experiment ends.

Some explanation of the rationale behind experiment 3 and its relationship to experiment 2 is perhaps necessary at this point. On the face of it, experiment 3 is a very peculiar tracking display, bearing no relationship to any lawful event which could happen in the real world (adults in fact typically describe it as surreal). It is however closely related to the display used in experiment 2 in terms of identity theory (see above). Both displays can be described in exactly the same spatial and temporal terms. In experiment 2 the same object is involved throughout whereas in experiment 3 a total of seven different objects appear sequentially at different places and at different times during the display. If we examine carefully the identity rules given above, the relationship between the two experiments becomes clear. In experiment 2 a young infant would be expected to attribute a different identity to the object any time it either moved or stopped or had the integrity of its boundaries violated in some way (in this case, by coming into a close spatial relationship with another object, the platform). In experiment 3, just such a change is actually produced (tachistoscopically) at each of these points in space and time.

At stage 1 of experiment 3 the model finds a new object each time either rest, motion or boundary violations change—nine objects in all. Stage 2 finds new objects each time size, shape, colour, or boundary violations change—nine objects in all. Stage 3 finds new objects only when size, shape or colour change—again nine objects in all.

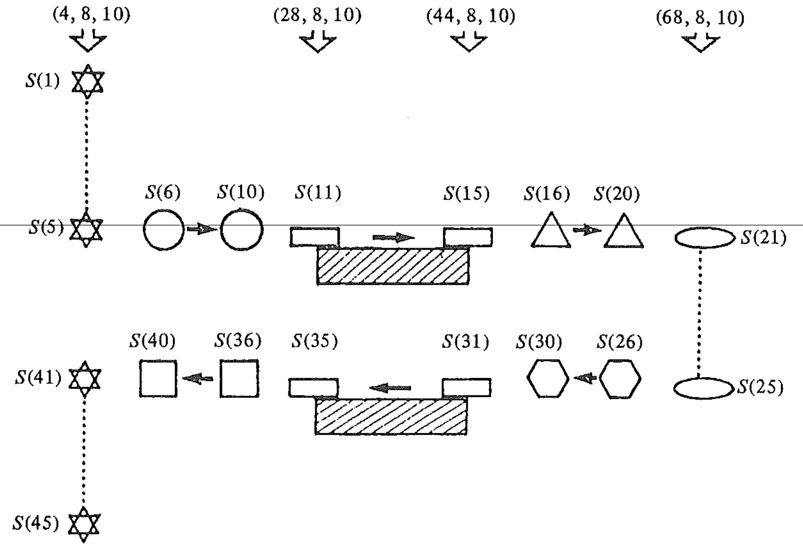

Figure 3. The snapshots of experiment 3. The colour and size of the objects are described in the text.

Table 3 summarizes the objects found and the justification for all stages by the computer model.

The empirical study related to experiment 3 is now completed and on a first-level analysis, the match between the performance of the model and actual infant behaviour at all three stages of development is satisfactory. As the computer predicted, during the course of the empirical study infants at each of the three stages identified a different object at all change points, following the new object and then glancing back to where the object change had occurred.

There are, however, limitations on the accuracy of the computer model's behavioural predictions for experiment 3. Real babies and the computer model both register the same number of identity changes at each stage in development. According to identity theory the conceptual rules for attributing change (and the acceptability or lawfulness of these changes) will differ over stages. In stage 1, for example, the infant registers a change in identity between objects 1 and 2 simply because a previously stationary object has moved (see table 3); the featural transformation of the object is completely ignored. By contrast stage 2 and 3 infants register a change in identity at this very same point precisely because of this latter change. According to the identity theory of object-concept development, all three stages of infants should identify the same number of changes in objects in this particular situation. However, researchers might expect differences in reasons for attributing identity change to be reflected in some way in the tracking behaviour of infants at different stages in development.

Table 3. The results of all stages of experiment 3.

Object number	Time	Reason
Stage 1		
1	1-5	object at rest
2	6-10	object in motion
3	11-15	boundary violation (object plus occluder)
4	16-20	end of violation/object in motion
5	21-25	object at rest
6	26-30	object in motion
7 (same as 3)	31-35	boundary violation (object plus occluder)
8	36-40	end of violation/object in motion
9 (same as 1)	41-45	object at rest
Stage 2		
1	1-5	star
2	6-10	sphere
3	11-15	boundary violation (rectangle plus occluder)
4	16-20	triangle
5	21-25	ellipse
6	26-30	hexagon
7 (same as 3)	31-35	boundary violation (rectangle plus occluder)
8	36-40	cube
9 (same as 1)	41-45	star
Stage 3		
1	1-5	star
2	6-10	sphere
3	11-15	rectangle
4	16-20	triangle
5	21-25	ellipse
6	26-30	hexagon
7 (same as 3)	31-35	rectangle
8	36-40	cube
9 (same as 1)	41-45	star

In the infant study this is just what was found. All stages of infants *at some time* during the eight presentations of this tracking task did show confusion at each object change point. Within any one trial, however, higher-stage infants generally made a greater attempt to relocate *every* disappearing object—that is, they double checked a greater number of object changes than their younger counterparts. Younger infants frequently showed little evidence of registering more than a couple of the object changes on each trial, smoothly tracking through other object changes unperturbed. This difference was especially marked in the earliest of the eight trials given. There was also some evidence that older infants would attempt to relocate not only the object which had just mysteriously disappeared but also the other objects which had disappeared earlier in the sequence. Younger infants rarely attempted to relocate any object other than the one which had just disappeared.

The present model is insufficiently refined to cope with such finer-grain distinctions in performance. Although all three stages of infants appear capable of registering the same number of changes in object identity, their methods of responding to these changes are quite different on a number of counts. Any future computer model must attempt to reflect these differences more accurately, possibly by building in a differential perceptual processing and memory capacity for each stage. A more sophisticated memory would also reduce the number of objects identified by the computer both within and over trials of experiments 1 and 2. While it is difficult to imagine exactly how infants would behaviourally index recognition of the sameness of, say, objects 1 and 5 in experiment 1 or objects 3 and 7 in experiment 2 (see tables 1 and 2), the literature on infant memory suggests that this would indeed be within the capacities of probably even the youngest subjects being considered here (see, for example, Bower 1967; Fagan 1973; Olson and Sherman 1984).

5 Discussion

As can be seen in the previous section, the computer model embodies the conceptual rules presumed to direct the search behaviour of infants at all three stages of object-concept development. The output of this model fits well with the actual behaviour produced by infants who took part in experiments 1 and 2 (see Bower and Paterson 1973; Wishart 1979; Bower 1982) and to a lesser extent with the behaviour found in experiment 3 (Bower 1983; Wishart and Bower 1984b).

A motivating force in the design of our model has been to demonstrate that the presence of different perceptual invariants across the object structures that make up both the experiment snapshots and the infants' experience allows two powerful explanatory mechanisms for characterising development. First we hypothesize that the psychological effect of formally describable relations such as motion, rest, and boundedness is to produce the behaviours that allow us to discern the three distinct stages of development. That is, the infants' tracking behaviour is directed not by 'direct' perceptual input but by three sets of conceptual rules (here encapsulated in PROLOG clauses) discerning the invariants found across the object structures of the experiments.

Second, we hypothesize that the high cost of coping with multiple 'objects' (a plethora of nonintegrated perceptual phenomena) at one stage of development gives way with the discovery of new perceptual invariants at the next stage to a more economical accounting. The discovery of new invariants provides a more parsimonious explanation for the same phenomena. This cost/gain explanation (Bower 1982) for between-stage development is the main focus of our continuing research, with the model and with babies. At present we know that infants exposed to tasks like experiment 2 described above will show accelerated development through the stages.

The acceleration is manifested not only in simple visual tracking tasks but also in transfer tasks involving manual search (Bower and Paterson 1973; Wishart 1979; Bower 1982). The fact of acceleration in the transfer tasks gives us confidence that the changes induced by tracking experience are conceptual changes, rather than changes in sensori-motor skill. Our hypothesis is that the motive force of change is the conceptual gain associated with the reduction in the number of objects the cognitive system must deal with at each successive stage. The 'cost' of this 'gain' is the increased load the perceptual system must bear. With experiment 2 there is a clear gain. With experiment 3, by contrast, there is no gain whatsoever from a change in the coding rules. Thus whereas we know that experiment 2 will produce acceleration in visual tracking and transfer tasks, we would expect experiment 3 to have no such effect. Although a certain amount of acceleration in performance on transfer manual object-permanence tasks was produced by regular exposure to this tracking task, the degree of that acceleration was not significant and indeed small enough to be explained as a simple Hawthorne effect arising from regular laboratory visits and frequent exposure to the transfer tests. Both qualitatively and quantitatively, the acceleration found bore little relationship to the acceleration found in experiment 2 (Bower 1983; Wishart and Bower 1984b). We now intend to use the detailed results from these two experiments to build a cost/gain metric into the model. If the metric can reproduce the patterns of acceleration already obtained empirically, we will run the computer model using other possibly accelerative tracking displays and then test the best of these with real babies.

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APPENDIX

A more detailed description of the PROLOG model running experiment 2

In the first step of an experiment the object structures are created. In experiment 2 there are two objects. The first, a green cube, moves to the right and then to the left across the field of vision, resting for a period of time at either end of its path of movement. The second object is an occluder, a black platform, stationed permanently in the middle of the first object's path.

First, a structure to represent the first object at time 1, is created on the left side of the field of vision and centred at (x, y, z) coordinates of (4, 8, 10) where it remains for four further time periods. This object is a green cube of size 2. The height and width of the cube will thus be 4 units. The movement to the right is horizontal, that is, the x coordinate changes from 4 to 68 (4 units at a time) while the y and z coordinates remain constant at 8 and 10 respectively. It then stops at the point (68, 8, 10) for five time periods. Then the cube retraces its path, 4 units at a time, until it returns to (4, 8, 10), to remain at rest until the experiment ends. The occluder (the second object) remains stationary in the centre during the entire experiment at coordinates (36, 4, 6). It is black, 6 units high and 8 units across. The infant is located directly in front of the occluder at (36, 0, 0) throughout the experiment. The green cube and the platform share a common space from the view of the infant from time periods 11 through 15 and 31 through 35. (See figure 2 in the text for a pictorial representation.)

Each snapshot contains a list for each object present during the time period. The list for each object contains a name, a location, and the size, colour, and shape for each object. At time 7, for example, the snapshot contains the two object names and their respective property lists:

```
OBJ-time 7            OBJ-time 7
location (12, 8, 10)  location (36, 4, 6)
shape (cube)          shape (occluder)
size (2)              size (4)
colour (green)        colour (black) .
```

With the information present in the snapshots such things as motion, rest, shared space, and perceptual cues can be determined by the subject looking for regularities across snapshots.

The second part of the experiment calls a set of PROLOG procedures (representing the infants' competencies at each stage—see text) to analyze the snapshots created in the first part. Only the clauses from one developmental stage consider the snapshots at any one time. The sets of clauses for each stage (see section 3) are part of a larger call that starts at snapshot 1 and goes by single steps to snapshot 46. Each statement in the trace that follows is only indicative of the results of testing each competency.

The trace for experiment 2, stage 2 follows, with ellipsis (...) indicating a repetition of the preceding statement.

```
Object 1 has interest at time 1
and is expected at location (4, 8, 10)
the cube has no boundary violation at time 1
```

```
Object 1 has interest at time 2 and is ...
⋮
Object 1 has interest at time 6
new object called object 2 is found at (8, 8, 10)
look again for the old object 1 expected at (8, 8, 10)
size, colour, and shape indicate the object is unchanged
the cube has no boundary violation at time 6
Object 1 has interest at time 7
and is expected at location (12, 8, 10)
the cube has no boundary violation at time 7
Object 1 has interest at time 8 ...
⋮
Object 1 has interest at time 11
and is expected at location (28, 8, 10)
the cube begins a boundary violation at time 11
call this object 2 and look back to previous object
Object 2 has interest at time 12 ...
⋮
Object 2 has interest at time 16
and is expected at location (48, 8, 10)
the cube ends a boundary violation
call this object 3 and look back to previous object
Object 3 has interest at time 17 ...
⋮
Object 3 has interest at time 21
new object called object 4 is found at (68, 8, 10)
look again for the old object expected at (68, 8, 10)
size, colour, and shape indicate the object is unchanged
the cube has no boundary violation at time 21
Object 3 has interest at time 22 ...
⋮
```

The object starts again from rest and returns across the occluder to rest at (4, 8, 10) at time 45 at which time the experiment ends.

The trace for stages 1 and 3 are similar for this experiment with the trace indicating the effect of the PROLOG clauses making up the description of each of these stages.