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TEMPORAL REASONING: WHAT DEVELOPS?

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How is time handled in kinematic and non-kinematic events from childhood to adulthood? Do subjects take one dimension or two dimensions into account to infer a third relationship? What occurs when the temporal information is presented in a hypothetical form (premises and conclusion)? A theoretical model based on empirical data from children, adolescents and adults is presented to describe the organization and development of relations across three dimensions in kinematics (i.e., relations between time, velocity and distance) and non-kinematics (relations between duration, beginning and ending times). The basic assumption of the model is that "temporal dimensions" are combined pairwise (dyadic relations) within *structurally stable* and *structurally unstable* cognitive systems, before yielding to undecidability concept (last level of triadic relations). Some predications of the model for decidable and undecidable time problems are presented. Data analysis shows that, even for adults, the concept of undecidability is constructed much later for non-kinematic events (i.e., in problems concerned with duration and succession) than for kinematic events when the information is presented in a hypothetical form (written or oral statements).

Temporal reasoning and temporal representation, in both theoretical and applied forms, is a very active area of research in Cognitive Science nowadays (Richards, Bethke, van der Does & Oberlander, 1989; Shoham, 1988). What do we know about the development of temporal reasoning from childhood through adulthood from the point of view of cognitive psychology? The French language psychology has a long tradition, dating from Guyau (1902), of studying time concepts and temporal reasoning (see Michon, Pouthas & Jackson, 1988). For the last twenty years, the study of the development of temporal reasoning, which is rooted on Piaget's classical research (Piaget, 1946a,b), genetic epistemology studies (Bovet, Gréco, Papert & Voyat, 1967; Grize, Henry, Meylan-Backs, Orsini, Piaget & Van Den Bogaert-Rombout, 1966) and Fraisse's studies (Fraisse, 1967, 1982) has been approached by using several different methodologies and conceptual frameworks. These include the method of rule-assessment within the sequential decision theory (Acredolo, 1989; Siegler & Richards, 1979), functional measurement within the framework of information integration theory

(Anderson & Wilkening, 1991; Wilkening, 1981), the facet model (Levin, 1977, 1982), the "neopiagetian" approach with specific characteristics in the type of situation presented and in the level of analysis (Montangero, 1977, 1979; Montangero & Gurtner, 1983), and the author's work based on a structural stability model (Crépault, 1975, 1983, 1989). These new paradigms, which explore both kinematic and non-kinematic phenomena, have served to renew Piaget's methodology and conceptual frameworks, and have raised new issues concerning the development of the concept of time (see Friedman, 1989; Montangero, 1984; Levin, 1992). In spite of the diversity of approaches, the results of the different experiments share some common characteristics: 1) behaviours related to time develop with age (from childhood to adulthood); 2) behaviours can be related both to external (e.g., cues of the situation, verbal help, school curriculum, etc.) and internal factors, such as the level of organisation of the inference, the meaning of the cues for the subjects, and the search for coherence (Crépault, Jacquet, Levin, Montangero, Pouthas & Wilkening, 1983). The method of rule-assessment led to the conclusion that even 11-year-olds lacked functional understanding of duration, whereas the functional measurement method suggested that such understanding existed in 5-year-olds. Also, Siegler and Richards's (1979) data led to the conclusion that adults used the physical rule (R3: Speed = Distance/ Time), whereas Wilkening's results suggested a subtracting rule for speed (Speed = Distance - Time) (Anderson & Wilkening, 1991). However, we are not certain that these authors all refer to similar processes or levels of behaviour. One of the basic problems of developmental cognitive psychology concerns the description and explanation of the mechanisms of transition. Are certain states of knowledge unstable? According to Piaget's classical experiments on time the "intermediary levels" seem to reflect this character of conceptual instability. Likewise, the third relevant rule postulated by Siegler (1981) for the "formal tasks" is of the same nature. The recent neopiagetian models (see Case, 1991; Halford, 1993) generally postulate a certain degree of coherence at each level of development. According to our main developmental hypothesis, development is characterised by alternating structurally stable and unstable cognitive systems. This paper presents a description of the author's approach to cognitive development, which is grounded on the concept of *structurally stable* and *unstable cognitive systems* (composition of three pairs of dyadic relations within cognitive systems). Questions on the development of temporal reasoning such as: are certain states of knowledge more stable than others? what criteria should be used to differentiate stable and unstable cognitive systems? are explored as regards firstly, the relationships between speed, distance and time and, secondly, the relationships between duration and succession.

TOWARDS A NEW PARADIGM OF TEMPORAL REASONING

The classical paradigm

Most of the work on temporal reasoning -the relations between duration and succession- has been restricted to special classes of situations (Levin, 1977, 1992; Montangero, 1977, 1981; Richie & Bickhard, 1988). For example, in duration and succession problems, the classical experimental paradigm consists in presenting a child with information concerning the successions [beginning (t1) and end times (t2)] of two bulbs which each switch on and off. The "bulb" display yields four problem types: 1) simultaneous [t1= & t2=], 2) ending [t1= & t2≠], 3) beginning [t1≠ & t2=], and 4) non-simultaneous types [t1≠ & t2≠], where the subject is asked to judge the relative duration of the bulb. One of the major findings is that the majority of 4-5 year olds respond correctly on beginning and ending time situations. Furthermore, recent data suggest that children perform better on ending time situations than on beginning time situations (Levin, Israeli & Darom, 1978; Montangero, 1981; Samartzis, 1992). Young children are able to recall succession for ending and beginning time situations but they fail to integrate information about initial and final temporal orders to infer relative duration (Levin, Goldstein & Zelniker, 1984).

The hypothetical situation paradigm

We present a new experimental paradigm of temporal reasoning, comparable to the paradigm used in syllogistic reasoning tasks -premises and conclusion, but without a middle term- (Johnson-Laird & Byrne, 1991). In many physical situations, such as problems with three variables, the steps preceding the mastery of quantitative relations are characterised by the use of *qualitative relations* (Crépault, 1981a, 1989; Crépault & Samartzis, 1989; Gréco, 1967; Inhelder & Piaget, 1955). In the case of problems with three variables (qualitative

relations), one can define either decidable wordings or undecidable wordings (27 couples of relations). In the first case, the information obtained allows the inference of only one correct relation, whereas in the second case, three undecidable or undetermined relations are possible. It should be remembered that in the case of the physical model (triadic model), the undecidability naturally concerns the third variable. For instance, in the balance beam problem (the balance scale has two dimensions: the amount of weight (W) on each side of the fulcrum, and the distance (D) of the weights from the fulcrum), children using Rule IV consider both dimensions and compute the torques (Weight X Distance) on each side if such a computation is necessary (Siegler, 1981). In qualitative reasoning, the premises "Heavier (W+)" and "Less distant (D-)" (on one side of the beam) lead to a state of indecision. Thus three states of the physical system are possible, for example:
- 4W x 3D = 3W x 4D (equilibrium);
- 5W x 3D < 4W x 4D (the side with greater distance goes down);
- 4W x 4D > 3W x 5D (the side with more weight goes down).

In kinematics, the premises "Faster " and "farther distance" (for some mobile X) leads to a state of indecision concerning their relative durations; for example, travelling a farther distance at a faster speed may lead to a longer, shorter or same duration. In time-succession problems, the premises "Started after" and "Stopped after" (e.g. *The red light goes on after the green light* and *The red light goes off after the green light*) entail three possible answers related to duration. However, certain pairs of relationships are decidable (they lead to a single correct response). Some examples of *decidable problem* are: "Heavier (W+)" and "More distant (D+)" (on side X, balance beam problem); for example, the side with greater distance and greater weight goes down (4W x 4D > 3W x 3D); "Faster" and "Less distance" (for some mobile X) leads to a shorter duration; "Started after" and "More time" (for example, *The red bulb goes on after the green bulb* and *The red bulb stays lit longer*) leads to a single correct response *(the red bulb goes off after the green bulb*). In problems with three variables, twenty-one pairs of relationships are decidable (one possible answer) and six pairs of relations are undecidable (three possible answers). Note that undecidable problems change into decidable ones within a metric (quantitative relationships): for duration-succession problems, there is an additive structure across three dimensions and a multiplicative structure for time-speed-distance problems. In this model, the *qualitative structure* (stable/unstable cognitive systems) is the same in the kinematics and time domains (Crépault, 1989). In triadic models, the subject integrates the two given dimensions (e.g., speed and time; beginning times and duration, etc.) and uses the two relations to infer the third. In dyadic models, only one dimension (e.g., speed or time, duration or beginning times, etc.) is used to infer the third.

Towards a model of temporal reasoning

General knowledge and inferred knowledge

The model described below relates to empirical and theoretical studies concerning the cognitive development of temporal reasoning in children, adolescents and adults (Crépault, 1979, 1980, 1981b, 1989). The model applies to classes of situations that have three physical or non-physical dimensions (e.g., time, distance, velocity; duration, beginning and ending times, etc.). The guiding hypothesis is that there are two main types of knowledge that individuals apply to a given situation. On the one hand, there are general knowledges (GK) which are applied to several fields of cognition (kinematics cognition, spatial cognition, physical cognition, etc.). On the other hand, there are inferred knowledges (IK) based on general knowledges and the characteristics of the task (instructions, experimental interview, questions, etc.). These two types of knowledge are interdependent; i.e., part of the GK can be replaced by IK and thus produce new GK. What are the relationships between general knowledge and inferred knowledge?

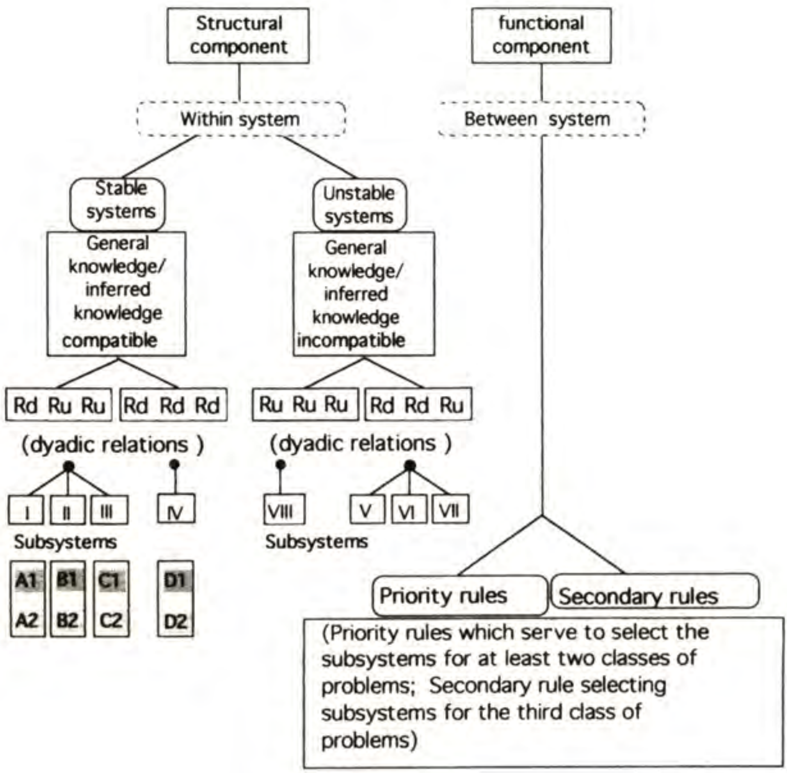
Structurally stable and unstable cognitive systems

Two basic mechanisms are assumed to operate between general and inferred knowledge.

1. When GK and IK are compatible, the cognitive system is termed *structurally stable* because newly constructed relations (inferred relations) are similar to the initial relations in the general state of knowledge.
2. When GK and IK are incompatible, the cognitive system is termed *structurally unstable* because the inferred relations and initial relations are contradictory. In the case of unstable systems, the model applies two mechanisms to eliminate certain knowledge states. Either IK is eliminated but the GK remains, or IK replaces part of the GK. In this case,

there emerges a new organization of general knowledge which is structurally stable.

DYADIC MODEL FRAMEWORK



Rd: Decidable dyadic relations. **Ru:** Undecidable dyadic relations.

FIG. 1

Dyadic model framework

The model assumes a dyadic composition of symmetrical relations; i.e., variables are composed two by two (Crépault, 1975, 1978, 1989). Generally, stable and unstable cognition systems are defined by any composition of three pairs of decidable or undecidable dyadic relations, respectively, Rd and Ru (see Figure 1). For example, in kinematics, the direct relationship between velocity and distance is independent of the third variable (time). It should be emphasised that the distinction made here between decidable (Rd) and undecidable relations (dyadic model framework) reflects *decidable* and *undecidable wordings.* In triadic problems there can be decidable wordings (21 pairs of relations) and undecidable wordings (6 pairs of relations). In the first case, the information obtained can only yield one correct inferred relation, whereas in the second case three relations are possible (undecidable problems). In the case of a physical model (triadic model) undecidability naturally concerns the third variable. For example, in temporal relations, the premises "Started after" and "Stopped after" (*The red light goes on after the green light* and *The red light goes off after the green light*) entail three possible answers related to duration. In the model here, dyadic decidable relations (Rd) or dyadic undecidable relations (Ru) are defined by pairs of relations of two variables (e.g. "After [t1]" entails "After [t2], "Before [t1]" entails "Less time", etc.).

Stable cognitive systems

Stable cognitive systems are defined by the following basic components (three pairs of dyadic relations):

(1) {Rd, Ru, Ru } (three possible subsystems)

(2) {Rd1, Rd2, Rd3} (only one system)

The first general system (1) is characterised by a *dyadic decidable relation* (Rd) and two *dyadic undecidable relations* (Ru); three subsystems are thus possible (see Figure 1):

(3) {Rd1, Ru2, Ru3}, {Rd2, Ru1, Ru3} and {Rd3, Ru1, Ru2}.

In both systems, the deduced relation (inferred knowledge), based on two symmetrical dyadic relations, is part of the system:

(4) [Ru 0 Rd = Ru]; [Ru 0 Ru = Rd]; [Rd 0 Rd = Rd]

The symbol 0 indicates an operation of composition (transitive rule). The following are some examples of stable systems. In kinematic reasoning, undecidable relations (Ru2 and Ru3) are defined respectively by the direct relationship between distance and time (D-T) and the inverse relationship between velocity and time (V/T); the decidable relation (Rd1) is defined by the inverse relationship between velocity and distance (V/D). Within a stable system, the composition of the relation (V/T) with the relation (D-T) enables the construction of a new inverse relation (V/D') which is compatible with the initial relation (V/D). In other words, in the first step, the inferential schemes *faster entails less time* (Ru2) and *less time entails less distance* (Ru3) are activated. In the second step, these two schemes are combined to produce the inverse relation between velocity and distance (*faster entails less distance*), the latter being compatible with the initial relation (V/T) of the initial system {Rd1, Ru2, Ru3}. What predictions can a stable system make? How does one arrive at a judgement concerning a subject's level of knowledge? If the subject's first answer is akin to: "Faster: less distance", according to the model, only responses such as: "More time: more distance" can be predicted. For the inverse relationship between time and distance (Rd2), which is specific to the system {Rd2, Ru1, Ru3}, the model only predicts answers such as: "Faster: more distance". Once the subject's first answers are known, the theoretical model can predict the successive responses, by transformational invariance (Crépault, 1989).

Unstable cognitive systems

The unstable cognitive systems are defined as follows:

(5) {Ru, Rd, Rd} (three possible subsystems),

(6) {Ru1, Ru2, Ru3} (only one system)

System (5) is characterised by three subsystems (see Figure 1):

(7) {Ru1, Rd2, Rd3}, {Ru2, Rd1, Rd3} and {Ru3, Rd1, Rd2}.

System (6) is characterised by three dyadic undecidable relations (Ru). Note that by the formal properties of the system {Ru1, Ru2, Ru3}, the two dyadic undecidable relations entail a new dyadic decidable relation:

(8) [Ru1 0 Ru2 = Rd3

The new relation (Rd3) is then incompatible with the "initial relation" (Ru3) of the system. The system is then transformed:

(9) {Ru1, Ru2, Ru3} → {Ru1, Ru2, Rd3} or {Ru1, Ru2, Ru3}

(9') *unstable system* → *stable system* or *unstable system*

The following are some examples of unstable systems. Consider system {Ru1, Ru2, Ru3} within the context of kinematics reasoning. Undecidable dyadic relations (Ru) can be assumed to correspond to the following relations: direct relationships between velocity and distance (V-D) or between distance and time (D-T), and inverse relationships between velocity and time (V/T). Within the unstable system, the relation deduced from the inverse velocity-time relation (Ru1) and the direct velocity-distance relation (Ru2) lead to the new inverse relationship between time and distance (Rd3) which is incompatible with the (initial) direct time-distance relation (Ru3). Two mechanisms of elimination are possible at this point: either the dyadic relation (Ru3) is eliminated, which would then transform the system from a structurally unstable state into a structurally stable state, or the inferred relation (Rd3) is eliminated and the original state of knowledge (unstable state) is maintained. Finally, one would expect that the number of responses for unstable cognitive systems would be reduced by one half at each trial, since two states are possible (stable or unstable states). Note that the model predicts only one answer when the cognitive system is stable. An important aspect of the model is that the dyadic relations can become a "conceptual obstacle" that is eliminated over the course of cognitive development to allow for a triadic construction of qualitative relations i.e., a structural change from dyadic to triadic relations (Jarrige, 1992).

Structural and functional components

So far, the structural component of the model has been defined in terms of stable or unstable cognitive systems. For example, within the kinematics domain the cognitive subsystems for the inverse relation between velocity and distance have been defined (Crépault, 1989):

(10) Gamma 1 subsystem: {[V+D-], [D-T-], [V+T-]}
(11) Gamma 2 subsystem: {[V-D+], [D+T+], [V-T+]}
(12) Basic structure: {Rd, Ru, Ru}

The functional component covers the processes applied at the level of subsystems in the case of three classes of hypothetical situations (see Figure 1). The following are some examples for kinematics problems: Inference about duration (premises: "Velocity & Distance"), distance (premises: "Velocity & Duration") and velocity (premises: "Distance & Duration").

Two types of rules (meta-rules) can be postulated:

1. *Priority rules* (R-1) which serve to select the subsystems for at least two classes of problems (e.g., R-VELOCITY: priority rule for premises "Distance & Velocity" or "Duration & Velocity");

2. *Secondary rules* (R-2) selecting subsystems for the third class of problems, e.g., R-DISTANCE: secondary rule for premises "Distance & Duration".

APPLICATIONS AND PREDICTIONS OF THE MODEL

Temporal stable subsystems

Examples of structurally stable cognitive systems for the relation between duration (Δt) initial succession order (t1) and the final succession order (t2) are presented for two large classes of hypothetical situations: decidable and undecidable wordings. The three cognitive systems are defined as follows (see Figures 2 and 3). The symbol AF designate the relations "The red bulb goes on (off) AFTER (AF1 or AF2) the green bulb"; the symbol BE designate the relations "The red bulb goes on (off) BEFORE (BE1 or BE2) the green bulb"; the symbol Δt indicate the relations "The red bulb shines for more time (Δt+) or less time (Δt-).

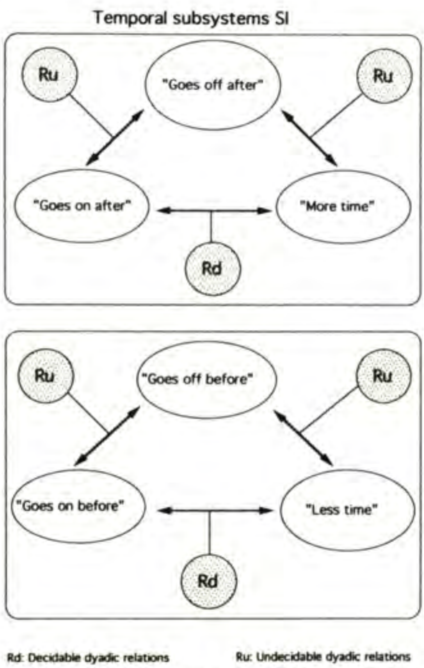


FIG. 2

System SI: Temporal subsystems SIAF & SIBE
(13a) SIAF = df. {[AF2 - AF1], [AF2 - Δt+], [AF1 - Δt+]}
(13b) SIBE = df. {[BE2 - BE1], [BE2 - Δt-], [BE1 - Δt-]}
The symbol "= df." indicates "equal by definition"
(13c) General system SI: {Ru, Ru, Rd}
System SII: Temporal subsystems SIIAF & SIIBE
(14a) SIIAF = df. {[AF2 - BE1], [AF2 - Δt+], [BE1 - Δt+]}
(14b) SIIBE = df. {[BE2 - AF1], [BE2 - Δt-], [AF1 - Δt-]}
(14c) General system SII: {Rd, Ru, Ru}
System SIII: Temporal subsystems SIIIAF & SIIIBE
(15a) SIIIAF = df. {[AF2 - AF1], [AF2 - Δt-], [AF1 - Δt-]}
(15b) SIIIBE = df. {[BE2 - BE1], [BE2 - Δt+], [BE1 - Δt+]}
(15c) General system SIII: {Ru, Rd, Ru}
These theoretical systems (SI, SII, SIII) exhibit the following characteristics for the relations between duration and successions .

System SI. The first system (see Figure 2) is characterised by non-differentiation between the beginning (t1) and ending times (t2); e.g., "More time" entails "Goes on after" [AF1 - Δt+] or "Goes off after" [AF2 - Δt+]. The symbols Ru and Rd indicate undecidable and decidable relations, respectively, that are associated with each pair of dyadic relations (e.g., Ru: "Goes off after (AF2) ↔ "Goes on after" (AF1) and "Goes off after (AF2) ↔ "More time" (Δt+); Rd: "Goes on after" (AF2) ↔ "More time" (Δt+). Two subsystems can be differentiated: SIAF (13a) and SIBE (13b). The composition of pairs [AF2 - Δt+] and [AF1 - Δt+], which are general states of knowledge, generate a new relation [AF1- AF2], which is compatible with the initial relation of general knowledge (13a or 13b). In other words, in the first step, the inferential schemes (dyadic relations) "Goes off after entails more time" (Ru: dyadic undecidable relation) and "More time" entails "Goes on after" (Rd: dyadic decidable relation) are activated. In the second steps, these two schemes are combined (operation of composition: [Ru 0 Rd = Ru) to produce a new dyadic indecidable relation ("Goes off after" entails "goes on after"), the latter being compatible with the initial dyadic relation (Ru) of the general state of knowledge. The same mechanism applies to subsystems SIBE (see Figure 3 for the subsystem selection within SI).

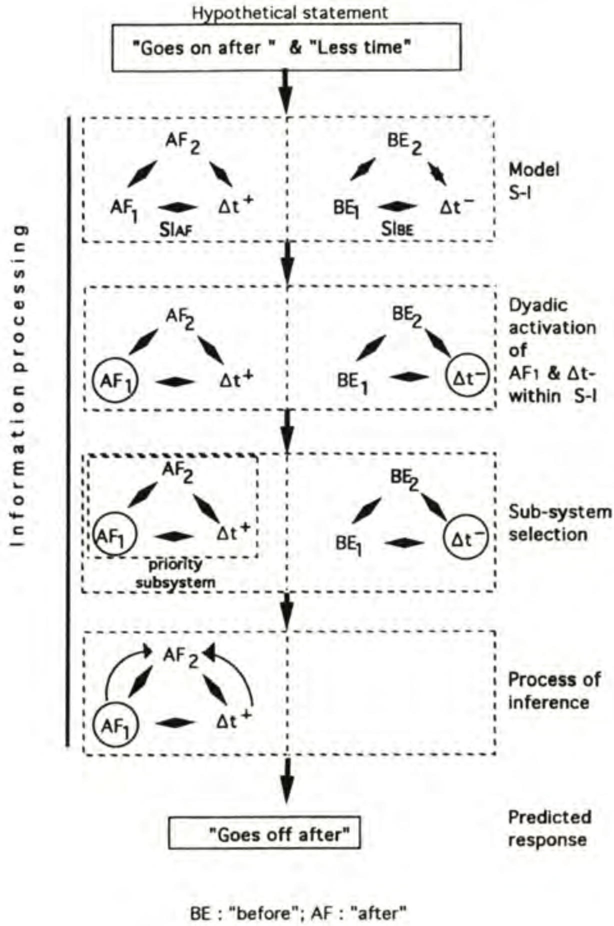


FIG. 3

System SII. Within system SII, the beginning and ending times are differentiated: e.g., "More time" entails "Goes on before" (BE1) or "Goes off after" (AF2). Subsystems SIIAF (14a) and SIIBE (14b) also represent three pairs of dyadic relations: The system is also structurally stable i.e., the inferred relation is compatible with the initial relation (general states of knowledge).

System SIII. The last system -not necessary at the highest level- is analogous to the first (13a) in that there is a non-differentiation of beginning and ending times: e.g., "More time" entails "Goes off before" (BE2) or "Goes on before (BE1). However, the duration (Δt) which is inferred from the beginning times (BE1 or AF1) is compatible with the physical model (e.g., "More time" entails "Goes on before" or "Less time" entails "Goes on after"). Naturally, the basic structure of SIII (15c) is common to systems SI (13c) and SII (14c) -stable cognitive systems: two dyadic undecidable relations and one dyadic decidable relation (Ru, Ru, Rd).

Some predictions of the model

Some examples of predictions for decidable and undecidable problems are presented below. Take the case of a subject who responds correctly on all decidable wordings (inequality problem types). How many theoretical systems are compatible with this kind of data? Previous studies have shown that at least twelve theoretical systems can be built. It is important to note that the twelve theoretical systems differ for undecidable wordings (Crépault, 1988; Crépault & Nguyen-Xuan, 1990). The following is a short description, in the framework of the relation between duration and succession, of the functional component (priority and secondary rules, see § 2.6) in the stable cognitive systems (12 theoretical systems). The twelve theoretical systems predict the same correct patterns for decidable wordings.

Theoretical subsystems SIAF and SIBE (4 models)
Model MI.1: R-1: Ending times (t2); R-2: Subsystem SAF
Model MI.2: R-1: Ending times (t2); R-2: Subsystem SBE
Model MI.3: R-1: Ending times (t2); R-2: Duration (Δt)
Model MI.4: R-1: Ending times (t2); R-2: Beginning times (t1)

Theoretical subsystems SIIAF and SIIBE (4 models)
Model MII.1: R-1: Duration (Δt); R-2: Subsystem SAF
Model MII.2: R-1: Duration (Δt); R-2: Subsystem SBE
Model MII.3: R-1: Duration (Δt); R-2: Ending times (t2)
Model MII.4: R-1: Duration (Δt); R-2: Beginning times (t1)

Theoretical subsystems SIIIAF and SIIIBE (4 models)
Model MIII.1: R-1: Beginning times (t1); R-2: Subsystem SAF
Model MIII.2: R-1: Beginning times (t1); R-2: Subsystems SBE
Model MIII.3: R-1: Beginning times (t1); R-2: Ending times (t2)
Model MIII.4: R-1: Beginning times (t1); R-2: Duration (Δt)

Note that each theoretical system can predict distinct individual configurations based on six undecidable wordings. Thus it is possible to choose specific responses for each subsystem. For example, in the case of premises " The red bulb goes on after the green bulb" and " "The red bulb stays lit for less time" (AF1 & Δt-), model MI (theoretical subsystems MI.1 or MI.4, Figure 3) predicts the response: "The red bulb goes off after the green bulb" (AF2).

Model MII (four theoretical subsystems) predicts the specific answer: "The red bulb goes off before the green bulb" (BE1). In the case of premises "The red bulb goes off before the green bulb" and "The red bulb stays lit for less time", model MI (four theoretical subsystems) predicts the response "The red bulb goes on before the green bulb" (BE1). Model MII (four theoretical subsystems) predicts the specific answer: "The red bulb goes off after the green bulb" (AF1). Model MIII (four theoretical subsystems) predicts specific answers [Δt+] for premises [AF1 & AF2], and specific answers [̆t-] for premises [BE1 & BE2]. Answers within one theoretical subsystem can also be analyzed. For example, rules R-1 and R-2 allows MI theoretical subsystems to predict eighteen patterns of responses, three of which yield identical answers (Crépault, 1988). The model thus serves to predict the sequence of responses based on the available cognitive system.

FINDINGS ON THE DEVELOPMENT OF TEMPORAL REASONING

How is time handled outside kinematics from nine years of age to adulthood? How will a subject process information when reasoning is based on hypothetical situations (decidable or undecidable time-succession problems)? This question prompted a series of experiments on several aspects of temporal reasoning in children, adolescents and adults (Crépault, 1988, 1989, 1992). The information (hypothetical statements) dealt with two dimensions: 1/ beginning and ending orders (inference about duration); 2/ duration and beginning orders (inference about ending orders); 3/ duration and ending orders (inference about beginning orders). Twenty-four hypothetical statements were presented (in French) to four groups of subjects (9, 12, 15 and adults).

Examples of wording problems

Some examples of the problems presented to subjects in written form appear below.

Inference about duration. Premises: beginning and ending orders
- a) BE1: "The red bulb goes on before the green bulb"; AF2: "The red bulb goes off after the green bulb";
- b) AF1: "The red bulb goes on after the green bulb"; AF2: "The red bulb goes off after the green bulb".
"Were the two bulbs on for the same amount of time or was one of the bulbs on for a longer time?" If a subject responds that the two bulbs were not on for the same duration s/he is asked to specify which bulb was on longer.

Inference about ending order. Premises: beginning order & duration
- c) AF1: "The red bulb goes on after the green bulb"; Δt+: "The red bulb stays lit longer";
- d) BF1: "The red bulb goes on before the green bulb"; Δt+: "The red bulb stays lit longer"

Inference about beginning order. Premises: ending order & duration
- e) Δt+: "The red bulb stays lit longer"; BE2: "The red bulb goes off before the green bulb";
- f) Δt+: "The red bulb stays lit longer"; AF2: "The red bulb goes off after the green bulb". "Did the two bulbs go on (off) together, or did one go on (off) first?". When the subject's response was one of non-simultaneity, the subject was further asked: "which of the two bulbs went on (off) first". Wording problems (a), (c), (e) are decidable (one answer), and wording problems (b), (d), (f) are undecidable (three possible answers).

Order of difficulty of wording problems

Data analysis (see Table 1) shows that:
- 1) Problems of the simultaneous beginning type (type t1=) are solved by about 12 years of age (85%). The errors observed in the 9 year-old children are of the type "The two bulbs are on for the same amount of time or the two bulbs go off together". Note that most of the young subjects (77%) make correct judgments on inequality decidable problem types (e.g., AF1 & Δt+: "The red bulb goes on after the green bulb" and "The red bulb stays lit longer").

Table 1. *Percentage of Correct Responses as a Function of Problem Type and Group* (N = 40 per cell)

	GROUP			
PROBLEM TYPE	9 yrs	12 yrs	15 yrs	Adults
Decidable problem types				
[AF1 & Δt+]	77	92	85	92
[t1= & Δt+]	57	92	97	97
[t1= & Δt+] & [t1= & AF2]	30	85	90	97
[Δt+ & t2=] & [BE1 & t2=]	17	45	70	82
[AF1 & Δt=] & [Δt= & AF2]	5	12	27	72
Undecidable problem types				
[AF1 & AF2]	0	2	12	40
[BE1 & Δt+]	0	0	10	40
[Δt+ & AF2]	0	0	5	42

AF: "AFTER" BE: "BEFORE" [=]: "Simultaneous or equal duration"
t1: Beginning times; t2: Ending times; [Δt]: Duration
Δt+: longer time; Δt-:less time

- 2) At the age of about 15, most subjects (70%) answer correctly on simultaneous ending problems. The errors observed in 12 year olds are of the type "Same duration or the bulbs that go on before take less time".
- 3) Problems involving "Same duration and non-simultaneity of events" (ending or beginning times) are solved only by adults (72%). The errors observed in preadolescents and adolescents are of the same beginning or ending times type: "The two bulbs go on (off) together".
- 4) Undecidable problems (e.g. "The red bulb goes on after the green bulb" and " The red bulb goes off after the green bulb") are very difficult and about 60% of adults fail to give three possible answers. Note that only 3 subjects (adults) out of 160 produced a correct response on the six undecidable problems.

Note that the data for the written form vs the oral form are fairly straightforward. Recall of the two sentences in written form is very poor in 9 to 15 year old subjects, as compared to the adult group. Recall of one sentence is very accurate at all ages (Crépault, 1988, 1992). Moreover, 70% of the answer patterns on undecidable problems (for subjects who responded correctly on inequality decidable type problems (N=73) was compatible with predictions of the model (systems SI, SII, SIII). Cognitively stable systems SI and SII predominate.

Conclusion

These results show that the relations of duration and succession create serious difficulties for adolescents and adults when the information is presented in a hypothetical form. What accounts for the enormous disparity between the early success of young children on duration of a physical display and the relatively weak results of adolescents on hypothetical statements (written or oral forms)? Task characteristics as well as the subject's available states of knowledge (general, inferred, empirical), and specific task knowledge or relevant knowledge about a field of concept, all play a role. Recent studies of neopiagetian models suggest that concepts of "structural stability" have rarely been tackled (Case, 1991; Halford, 1993; Karmiloff-Smith, 1992). Future studies should concentrate on whether the notions of stable and unstable cognitive structures can be applied to other physical contents. What links are there between temporal reasoning and other forms of reasoning, i.e., conditional reasoning, syllogistic reasoning and non-monotonic reasoning? The basic questions raised by Evans (1991) concerning 1) the mechanisms governing logical competence, 2) errors and biases in reasoning and 3) the impact of content and context, are as well relevant to studies dealing with temporal reasoning. Further, decidability and undecidability processes in temporal reasoning can be paralleled to the concept of "logical validity" in the mental-model theory (Johnson-Laird & Byrne, 1991) or the inference rule approach (Braine, 1990). From a broader standpoint the development of temporal reasoning needs to be characterised in the model by intersystem (structural changes or mental model change) and intrasystem transformations (functional changes or inference rule changes). Subjects at a given age can be assumed to act within a dynamic system (or mental models) based on several functional rules (or inference rules). This perspective implies that there are several developmental trajectories before reaching the triadic model, in particular the undecidability concept which is constructed much later by the adult (if at all!).

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