Journal of Experimental Child Psychology **77,** 138–154 (2000)
doi:10.1006/jecp.2000.2593, available online at http://www.idealibrary.com on IDEAL®

Reflections on Working Memory: Are the Two Models Complementary?

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By means of the theoretical modeling of data from Kemps, De Rammelaere, and Desmet (2000, this issue), the working memory theory of Baddeley and the theory of constructive operators of Pascual-Leone are contrasted and compared. It is concluded that although the theory of constructive operators is complementary with working memory theory (for it explains developmental and individual differences that working memory theory cannot explain), the converse is not true; the theory of constructive operators explains all the data without need of working memory theory.

Key Words: working memory; executive processes; mental attention; M-capacity; task analysis; Corsi task; Peanut task.

. . . no content can be grasped without a formal frame, and . . . any [theoretical, J. Pascual-Leone] form, irrespective of its previous usefulness, can prove itself too narrow to encompass new experimental data.

—Niels Bohr[1]

The paper by Kemps, De Rammelaere, and Desmet (2000, this issue) on "The Development of Working Memory: Exploring the Complementarity of Two Models" is an excellent empirical attempt to address, albeit in a controversial manner, an important issue: the possible complementarity of Baddeley's and Pascual-Leone's models of working memory. The manner is controversial, because methodologists might think that relations of complementarity among theories cannot be settled empirically but must be evaluated theoretically. There

Research on which this *Reflections* paper is based was supported in the last 10 years by operating grants from Social Sciences and Humanities Research Council (SSHRC) of Canada. The current SSHRC grant supporting this project was jointly awarded to me and to Dr. Janice Johnson. I am grateful to Janice, to Dr. Sergio Morra, and to Nancie Im-Bolter for insightful comments that have much improved this paper.

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[1] Translated by Juan Pascual-Leone from the original French: "il nous a appris une fois de plus qu'aucun contenu n'est saisissable sans un cadre formel et que toute forme, quelle qu'eût été jusqu'alors son utilité, peut se montrer trop "étroite pour embrasser des nouveaux faits d'expérience" (Niels Bohr, 1961, p. 106).

0022-0965/00 $35.00

are two senses of complementarity used in the psychological and scientific literature, although often in an unexplicated manner. According to the *empirical* (weak) *sense of complementarity*, two theories or models are complementary whenever they are jointly needed to account for some empirical facts, perhaps because the two theories have in part distinct domains of application, and at least one of them explains some aspect of the data that the other fails to account for. According to the *dialectical* (strong) *sense of complementarity*, two theories are complementary only when they meet three conditions: (C1) They are mutually contradictory in the sense that neither can be reduced to the other theory, at least while preserving its internal consistency. (C2) They are jointly needed to account for data at hand and/or to predict results. (C3) Each theory in some sense serves to control/modify/complete the predicted output or performance of the other, so that it must tacitly or explicitly be used to enable predictions from the other theory to succeed.

I take it that the empirical sense of complementarity is intuitively clear, and this is the sense intended by Kemps et al. The dialectical sense of complementarity (related to the physicist Niels Bohr's principle of complementarity) is less clear, and I should illustrate it with some relevant example. A case that is compelling, but often disregarded, is the dialectical relation of complementarity that exists between theories of learning and theories of developmental intelligence (in the broad sense of general problem-solving ability increasing as a function of organismic change with chronological age). A pure theory of developmental intelligence, such as Piaget's, tacitly needs a theory of cognitive learning to account for accommodation, because no explicit principles for accommodation are found in Piaget's theory. To see that condition (C3) above applies to this example, consider the methodological strictures that Piaget (or classic Piagetians) versus learning theoreticians use in designing their experiments. Piaget and classic Piagetians make sure that the task is novel and that the child has not acquired much experience related to it. Learning investigators, in contrast, make sure that the task is suitable to the children, in the sense that it is not too difficult or too easy—thus tacitly (and empirically) adjusting the variables of developmental intelligence (e.g., chronological age) along with the choice of participants for the task at hand. Notice that this example is very relevant here, because Baddeley's theory (*henceforth to be called working memory theory;* Baddeley, 1986, 1991) represents an enriched contemporary version of verbal learning theory, whereas Pascual-Leone's theory (*henceforth called theory of constructive operators*) is neo-Piagetian.

From the perspective of these two senses of complementarity, Kemps and her co-workers intend only the empirical sense of complementarity between the two theories. They make a plausible case, but to establish that empirical or a stronger sense of complementarity actually exists, one should attempt, and fail, to reduce each theory's data to the other theory. The authors' work has shown that the theory of constructive operators cannot be reduced to working memory theory,

because the latter theory lacks what I just called "developmental intelligence" constructs—constructs that can explain patterns of growth in performance as a function of age. It remains to be seen whether working memory theory could be reduced to theory of constructive operators, in the technical sense that theory of constructive operators' constructs can explain working memory theory's data on the spatial and the phonological/articulatory-loop domains of processing and learning. Only if this attempt should fail could one regard the theories as truly complementary.

My strategy in attempting to explain working memory theory's data within the theory of constructive operators is to use a variant of developmental task analysis available in my theory (i.e., dimensional metasubjective analysis—Pascual-Leone & Johnson, 1991, 1999, 2000) to explain the results reported by Kemps et al.

I organize my comments around the main empirical findings (f) presented in the paper, listed in six points from (f1) to (f6), and introduce theoretical notions as needed. A brief Conclusions section then offers final reflections.

CHILDREN'S RELATIVE PERFORMANCE IN THE CORSI AND PEANUT TASKS

(f1) According to Kemps et al., the developmental patterns obtained in both the Peanut task and Corsi's spatial memory span task are consistent with age-bound quantitative predictions of the theory of constructive operators, and cannot be explained by working memory theory. I accept their conclusion, although their data are just an illustration.

(f2) Performance level consistently was higher on the Corsi task than on the Peanut task. An important categorial distinction of the theory of constructive operators may help to explain this finding that Kemps et al. consider surprising. I refer to the distinction between *misleading situations* and *facilitating situations* (Johnson, Fabian, & Pascual-Leone, 1989; Pascual-Leone, 1987, 1989, 1995). A situation is misleading (or facilitating) when it elicits (or does not elicit) schemes that interfere with the task at hand. Developmental task analysis shows that (relative to each other) the Peanut task is misleading, whereas Corsi's task is facilitating. Kemps et al. give some relevant reasons: Peanut has 14 different possible places for relevant stimuli to appear, whereas Corsi has only 9; in Peanut the search of relevant stimuli for information pickup is self-driven, whereas in Corsi it is externally scaffolded (i.e., mediated) by the indicative finger of the experimenter. Kemps et al. give one more reason, which appears to be theoretically ambiguous: Body parts of the Peanut clown can easily be identified and labeled, but the blocks of Corsi are all identical and cannot be labeled; consequently, more to-be-inhibited associations would be evoked by the Peanut leads. This should be so, however, only when the to-be-inhibited associations are schemes elicited by object parts (parts of the Peanut body) that distract from, or interfere with, the recall of other object parts. On the other hand, research in

verbal learning, on "meaningfulness" vis-à-vis recall, has shown that multiple associations generally facilitate recall: On this account Peanut should be easier and not harder than Corsi (this seems particularly so from the perspective of working memory theory, because Baddeley's phonological loop should be more easily applicable to the Peanut than to the Corsi task).

A better way to show why Corsi is a facilitating task, while Peanut is a misleading task, is using a distinction available in current neuroscience (Goodale & Humphrey, 1998) and also available in the theory of constructive operators (Pascual-Leone & Johnson, 1999; Pascual-Leone & Morra, 1991). This is the distinction between two categories of constructs: space-and-action-related versus time-and-representation-related constructs. In the theory of constructive operators this distinction is formulated in terms of experiential space-structuring schemes (related to direct perception), which are helped by an innate "hardware" operator for the construction of "space" within visuomotor activities.[2] This effortless "space" operator (or *S-operator*) is used to address the visuomotor issue of "where" something is located in preparation for action, and "how" it can be acted upon (Goodale & Humphrey, 1998). In contrast there are the schemes of object structuring and of representational perception, which are aided (only aided) by an innate "hardware" operator for temporal structuring (called in my theory *T-operator*). This temporal-structuring operator is my name for the brain's mechanism that rather effortlessly (i.e., in the manner of "direct" perception) registers sequences of change in the momentary evolution of an object or input (consequently registering the change in relations among this and other objects), thus facilitating the empirical/reflective abstraction of the objects' meaning; consequently, as neuroscientists would say, helping to answer the "what" questions of visuo-representational perception and cognition (i.e., what is it?, what does it represent perceptually?, what orientation does it have?—all referring to something available in the situation; see Goodale & Humphrey, 1998; Pascual-Leone & Johnson, 1999; Pascual-Leone & Morra, 1991).

I can concretize the idea of these two operators by showing how they would apply in the Corsi task. The Corsi task is a facilitating situation (no misleading or irrelevant cues), and it is facilitated by both the *S*- and *T*-operators, primed and guided by the experimenter's indicative hand that helps in the information pickup. In the Corsi task the *S*-operator appears as the brain mechanism that, given a number of block-finger-pointing actions by the experimenter, will with little effort constitute a relational pattern of their *topographic* location. The *T*-operator appears in the Corsi task as a brain mechanism that, given a sequence of occurring events or changes such as the block-finger-pointing actions, will

[2] The neurophysiological substratum of this "direct" perception of relational space (i.e., of the topographical relations holding among objects located in the field of external experience) is the largely homomorphic mapping of stimulation from receptor neurons to their subcortical and cortical projections, which generally preserves throughout the topographical relations from receptor to cortical (or subcortical) neurons. The parietal lobe seems to be a site where this topographical relational patterning is abstracted or represented.

(with little effort) constitute a serial pattern of their *sequential* order. Clearly, the combined application of *S*- and *T*-operators should facilitate the short-term recall of limited sequences of experimenter finger-pointing moves that subjects must reproduce in the Corsi task (the limit in the number of recalled moves within a sequence depends on the subject's *M*-operator—as shown in the next section of this paper). The Peanut task, however, is a relatively misleading situation, as *M*-capacity tasks tend to be; indeed, it demands recognition of multiple objects (body parts) that may elicit schemes distracting the subject's information pickup, and yet no innate hardware operator or external aid (other than the *M*-operator's power to hyperactivate relevant schemes) is guiding this pickup. Notice that the *S*-operator could not be of help here because the body parts in Peanut are all well-learned constituents of another superordinate scheme, the overall peanut figure, and because all the parts are included in it, interference among these parts for recall would render the *S*-operator's facilitation insufficient.

The categorial distinction between misleading and facilitating situations is central to the theory of constructive operators. Tasks that demand sophisticated executives and the use of active, mental-attentional inhibition—this is the theory of constructive operators' *interrupt* operator—so as to suppress misleading schemes (this is the case of misleading situations) tend to restrict a person's recall to the capacity "slots" afforded by his or her *M*-capacity. In contrast, recall in facilitating situations can be aided by other constructive operators. Among these other constructive operators I mention task-relevant content schemes (products of contextual content learning—the *C*-operator), *automatized* logical-structural schemes (the products of structural patterning caused by more or less complex content/relational learning—what the theory calls *L*-structures produced by *LC* learning), the *S*- or *T*-operators mentioned above, etc. Finally, there is also the possibility, when *M*-capacity becomes saturated (i.e., overtaxed) with schemes to be boosted in their activation, of removing *M*-capacity from some previously boosted schemes (thus putting them out of *M*-space) and letting them instead begin to decay in their activation weight (*W*) within the *field of activation* (this is the set of all activated schemes in the repertoire). Schemes that are outside the *M*-space but in the field of activation (these activated-but-outside-*M* schemes constitute what I call the *field of decay*) see their individual activation weight *W* progressively eroded by at least two or three decay-promoting mechanisms (Pascual-Leone, 1984; Pascual-Leone & Goodman, 1979; Pascual-Leone, Goodman, Ammon, & Subelman, 1978; Pascual-Leone, Johnson, Goodman, Hameluck, & Theodor, 1981) that I state as follows:

(D1) With each mental operation (i.e., each allocation of mental-attentional energy) there is usually an active and central, albeit automatic, partial inhibition of the activation weight of schemes that are not currently being *M*-boosted—this is caused by *automatic interruption* that the attentional system imposes on schemes that are not attended to, when mental attention has been selectively allocated to other schemes (automatic interruption serves to selectively focus mental

attention whenever M-capacity allocation—and thus M-space—is changed). See Burtis (1982) and Morra (2000) for mathematical models based on this idea.

(D2) Because schemes are self-propelling (this is Piaget's principle of assimilation) they compete and interfere with each other when they are in the field of decay, that is, are activated but outside of M; consequently, the rate of automatic interruption produced by (D1) on each relevant scheme left outside M-space will be potentiated by interference among these outside schemes, which thus will increase the automatic interruption going to them with their number, that is, the number of relevant schemes found in the field of decay. This generalization is consistent with Morra (2000) and with unpublished mathematical modeling of an M-capacity task done in collaboration with Morra and Johnson.

(D3) Perhaps as a function of real time, the activation weight W of schemes will decay when they are outside the M-space—this is what theories of learning and memory have traditionally claimed. This mechanism might exist, but it would be very hard to separate experimentally from the previous two, which the theory of constructive operators has emphasized (Burtis, 1982; Morra, 2000; Pascual-Leone & Goodman, 1979; Pascual-Leone et al., 1978, 1981). The rate of decay of schemes outside the M-space, due to (D1) and (D2), can be estimated, and has led to mathematical modeling by Burtis (1982) and Morra (2000). Presentation of these results is beyond the scope of the paper, for it demands refined step-by-step task analyses (the sort that the theory of constructive operators calls M-constructions). Instead I shall use a structuralist or dimensional-analysis simplification stated by the following (D4) rule.

(D4) In facilitating situations, because they minimize the use of attentional interruption—which in turn minimizes the effect of (D1) and (D2)—subjects of all ages are usually able to retrieve from the field of decay, when needed, two schemes to use in the task. In misleading situations, however, subjects of any age can retrieve no scheme, or at most one scheme, from the field of decay—because attentional interruption is then stronger, and it maximizes the effect of (D1) and (D2). This rule can be illustrated empirically with the much-investigated case of forward digit span (a facilitating situation) versus backwards digit span (a misleading situation, because here the ingrained practice of repeating verbal material in a forward manner will interfere with backward recall, and in order to keep this habit in abeyance people must use attentional interruption). If k is the expectable M-capacity of an age group as predicted by the theory of constructive operators (Pascual-Leone, 1970; Pascual-Leone & Baillargeon, 1994), data on these tasks tend to show that forward digit span (FDS) exhibits across age groups an average passing rate of $k + 2$, whereas backwards digit span (BDS) exhibits a passing rate of k. For instance, 7-year-olds (who have an M-capacity of $e + 3$) recall 5 units on average in FDS but they recall 3 units in BDS.

It is for these reasons that Corsi's, a facilitating task, is easier than the Peanut task. A more explicit modeling of this explanation appears in the next section.

AGE DIFFERENTIALS FOR THE CORSI AND PEANUT TASKS

(f3) Comparison of developmental traces for correct performance in Peanut versus Corsi tasks shows that Peanut exhibits a pattern of difference between 8- and 9-year-olds, which is consistent with the growth in *M*-capacity within the theory of constructive operators. Corsi's task, however, shows a plateau of 4 units recalled from 7 years of age to 9–10 years. Working memory theory may account for these findings in a descriptive manner: as a pattern of growth of its spatial component system (VSSP) versus the growth of its verbal component system (PL). The theory of constructive operators adds to this description a more analytical (and so more falsifiable) causal explanation, which I summarize below.

Corsi's is a serial task, a modified span task; as such subjects are penalized unless in their response they touch the relevant blocks in the appropriate order. Serial recall, as verbal learning researchers made clear in the 1950s, involves the learning both of relevant elements and of their ordinal position (or their associations). This means that both the location of relevant blocks (indexed by the block-pointing gesture of the experimenter) and their ordinal position must somehow be retained in the task analysis. If both aspects were to be remembered with the help of *M*-capacity, the mental demand of Corsi items should be much greater than that of corresponding Peanut items. But in the theory of constructive operators this is not so, because both the *S*-operator and the *T*-operator, as discussed above, facilitate emergence in everyday life of automatized, purely experiential (Piaget's infralogical) structures which I call spatial *L-structures.* These spatial *L*-structures of the person permit the chunking (*LC* learning) of the relevant-block locations (indexed by finger moves of the experimenter, facilitated by the subject's *S*-operator) with their corresponding ordinal positions (facilitated by the *T*-operator). Call SerL (abbreviation of Serial *L*-structure) this *sequential* structure facilitated by both *S*- and *T*-operators. Mathematical logic helps to formulate how such a SerL structure can be constituted. One algorithm for constructing this sequence could be an operative scheme SEQ that binds together the sequence of a pair of blocks in immediate succession (i.e., an experimenter's finger move). By applying this SEQ operative repeatedly, and with the help of mental attentional capacity, the subject can coordinate into an experiential (Piaget's infralogical) "logical" (*L*-) structure, and then perhaps chunk, an ordered set of blocks (or finger moves), say, 4 or 5. Call SerL4 (SerL3, SerL5) one such L-structure or operator for binding together the order of 4 (3, 5) blocks (finger moves). Written in operator-logic notation SerL4 and SerL5 could take the following form:

(1) $\text{SerL4} := \text{SEQ}(\text{SEQ}(-_1, -_2)-_3)-_4$
(2) $\text{SerL5} := \text{SEQ}(\text{SEQ}(\text{SEQ}(-_1, -_2)-_3)-_4)-_5$

In these formulas the innermost sequence operator SEQ binds together two ordered blocks (or finger moves) b_1 and b_2 in the corresponding inner slots; then this pair b_1b_2 is ordered by means of a second SEQ operator with a third block

(or finger move) b_3, etc. Notice that so defined SerL4 (SerL5) could easily allow the ordering of 4 (5) blocks, because the last block b_4 (b_5) will be spontaneously ordered, given the degrees of freedom.

What would the mental demand be for learning easily these "software" operators? Clearly the child should be able to boost simultaneously with *M*-capacity both the set of needed SEQ operators and a suitable operative scheme, which coordinates their binding into a single compound operator SerL4 or SerL5. Thus the mental demand of SerL4 will be at least 3 symbolic *M*-units (i.e., *M*-demand = $e + 3$), whereas SerL5 will have an *M*-demand[3] of $e + 4$. Because of the predicted pattern of developmental growth in *M*-capacity (Pascual-Leone, 1970; Pascual-Leone & Baillargeon, 1994), the theory of constructive operators prescribes that SerL4 will not normally appear in a child's repertoire before he or she is 7 or 8 years of age, and SerL5 will not appear before 9 or 10 years of age.

Consider now how children who possess these (generic) Serial *L*-operators could handle the Corsi task. Notice that the generic Serial *L*-operators task analyzed above will have to be instantiated in every item, so as to include the specific blocks (or experimenter's finger moves) constituting the item in question. It is this instantiation that the task analyses below actually model. Readers who do not need more detail can skip the rest of this section.

If we call LOC the complex scheme for locating in space certain "objects" (blocks or finger moves of the experimenter) so as to later recall *and* indicate their location (or dynamic pattern), and use the affix # to signify that SerL is a functional *parameter* (i.e., an auxiliary function) of LOC, then the task analysis of expectable performance for 6-, 8-, and 10-year-olds could be represented as follows:

(3) 6-year-olds: $M[\mathrm{LOC}^{L1}(\{\#\mathrm{SerL3}\}_{S,T,L1}, \{b_1\}_W, b_3)]$
(4) 8-year-olds: $M[\mathrm{LOC}^{L1}(\{\#\mathrm{SerL4}\}_{S,T,L1}, b_1, \{b_2\}_W, \{b_3\}_W, b_4)]$
(5) 10-year-olds: $M[\mathrm{LOC}^{L1}(\{\#\mathrm{SerL5}\}_{S,T,L1}, b_1, \{b_2\}_W, \{b_3\}_W, b_4, b_5)]$

In these formulas, the terms inside *M*[. . .] represent schemes that are hyperactivated, either because they are boosted by *M*, that is, are inside the *M*-space, or because there are other sources of activation actually boosting the scheme into hyperactivation (these are two different mechanisms that together constitute working memory—Pascual-Leone & Baillargeon, 1994; Pascual-Leone & Johnson, 2000). In the latter case the schemes in question are placed inside braces { . . . } to signify that they are not inside *M*-space but rather inside

[3] In the theory of constructive operators the expression $e + 4$ (or $e + 3$) signifies that *M*-capacity, when assessed in terms of the number of distinct schemes that it can simultaneously boost into activation, is equal to "*e*"—that is, the *M*-capacity developed during the sensorimotor period and later used to maintain into activation the task's executive schemes (Pascual-Leone & Johnson, 1999)—plus 4 (or 3), which is the number of distinct symbolic schemes (other than executives) that the child of 9 to 10 (or 7 to 8) years of age can simultaneously boost into high activation using his or her *M* capacity.

the *field of decay* (that part of the field of activation which is outside *M*-space), and they carry subscripted to the second brace the source of activation for the scheme placed inside the braces. The sources of alternative activation listed are the *S*-operator, the *T*-operator, and the *L1* link indicating that SerL3 (or SerL4 or SerL5) is already an integral constituent of the spatial *L*-structure LOC-and-SerL and receives its activation from this *L*-structure, not needing further *M*-boosting. The formulas also show, subscripted as an alternative activation source, the total activation weight *W* of the scheme in question when it is place inside the field of decay (Morra, 2000; Pascual-Leone & Goodman, 1979), and this activation weight decreases progressively according to rules (D1) and (D2) given above. Because in facilitating situations children can retrieve from the field of decay up to two relevant schemes—see heuristic rule (D4)—the schemes placed inside braces with a subscripted *W* will be available for the child to retrieve, even though they are not boosted by *M*. For instance, in the formula for 6-year-olds, the Serial *L*-operator SerL3 is not being boosted by *M* but instead is being boosted by the *S*- and *T*-operators and the *L1* link, and in addition blocks b_1 and b_2 will be retrievable from the field of decay.

The *M*-demand of Formula (3) is $e + 2$; that is, 2 mental schemes (LOC and b_3) need to be boosted with mental *M*-capacity. This is the capacity first available to 5- and 6-year-olds. The *M*-demand of Formula (4) is $e + 3$ (7- and 8-year-olds), and that of Formula (5) is $e + 4$ (9- and 10-year-olds). Nine-year-olds should be able to generate Formula (4) but not Formula (5). This is because a mental *M*-capacity of $e + 4$ does not appear until 9 years of age and the *M*-demand of constructing SerL5 (see Formula (2)) is also $e + 4$. Because time is needed to develop it, SerL5 may not be available until 10 years of age (see Goodman, 1979, for a discussion of these structural readiness considerations). In this way Formulas (3), (4), and (5) explain quantitative results that Kemps et al. report in Fig. 3. The working memory theory cannot make these structural quantitative predictions.

VERBAL MEDIATION IN THE CORSI AND PEANUT TASKS

(f4) Kemps et al. find, as has been found before in many other tasks, that verbal encoding and rehearsal facilitate memorial performance in older children, but not in younger children—that is, articulatory suppression lowers performance in the Peanut task for older but not for younger children. Researchers of working memory theory have often used and expanded upon these findings, although they have not completely explained the mechanisms (Halliday & Hitch, 1988; de Ribaupierre & Bailleux, 1994). These data can be explained quite naturally within the theory of constructive operators, in a manner that throws light onto the development of verbal mediation.

Use of verbal mediation (this is Baddeley's "articulatory loop") to facilitate recall in tasks suitable for verbal encoding (e.g., the Peanut task) amounts to thinking of a serial linguistic-operative scheme SerLIN, constituted analogously

to SerL in Formulas (1) and (2) but using linguistic encoding. SerLIN can apply on content schemes (symbolized in the formula below by —) to implement linguistic/verbal encoding and "rehearsal." This "software" operator SerLIN would emerge as a consequence of language acquisition and linguistic imitation, with the support of the *T*-operator and of *M*-capacity. SerLIN can function as a tool (as a functional parameter of the task's procedure) in the task of location and recall of marked body parts on the Peanut's body. Let us now call LOC the task's superordinate location-and-recall operator, and call #pea the subject's representation of the Peanut's body frame.[4] The process-strategy formula corresponding to this idea might be as follows:

(6) $\mathrm{LOC}^{L1}(\{\#\mathrm{SerLIN}\}_{T,L1}, \{\#\mathrm{pea}\}_{LC}, —)$

A child well practiced in verbal mediation has in his or her repertoire a subjective operator (i.e., a compound operative scheme) LOC# symbolized in Formula (6) by the *L*-structure LOC-and-SerLIN, which contains within itself one parameter (parameters of this operative process are indicated in the formula by the affix #). This parameter is the operative scheme SerLIN, supported in its emergence by the *T*-operator—indicated in Formula (6) by writing *T* as a subscript to the braces enclosing SerLIN. A more sophisticated subject, after some practice in the Peanut task, might have developed instead the "software" operator LOC##, which would be similar to LOC# but also incorporate into its *L*-structure the scheme #pea as a second parameter. In Formula (6) #pea is shown outside LOC# (i.e., outside the *L*-structure LOC-and-SerLIN). The scheme #pea can be thought of as the representational frame or context where the verbal encoding/rehearsal operation takes place in the task—that is, the outline of Peanut's body. When a parameter is part of the operative *L*-structure LOC# (or LOC##), this being "part of"—chunked with, if you will—is indicated in processual task-analysis formulas such as Formula (6) by a superscripted/subscripted *L1*, which indicates the scheme parameter(s) which is (are) part of the *L*-structure (or complex scheme) in question. Because one (or two) #-marked scheme(s) is (are) part of the *L*-structure, once LOC# (or LOC##) is boosted with *M*-capacity its one (two) subordinate scheme(s) will become hyperactivated without the need of additional *M*-capacity. This is to say that LOC# (or LOC##) is a learned encoding/rehearsal mechanism ready to be applied on suitable content schemes (in the formula indicated by —) for their conjoint verbally mediated memorization.

Consider the *M*-capacity a subject must have in order to acquire on his or her

[4] The meaningful constructive abstraction of the object-outline Mr. Peanut and of its body parts (b_1, b_2, b_3, etc.) is facilitated by the temporal-structuring operator (*T*-operator) mentioned above, which helps to coordinate and integrate the eye-movements scan path that configures the outline as a totality. Once the meaningful Mr. Peanut has been learned, however, and can be recognized, the process of recalling the parts just seen in the current item is no longer dependent on temporal structuring, and so for this working memory task the *T*-operator does not intervene and will not be mentioned in the analyses that follow.

own, without much external help, these LOC# or LOC## verbal mediation operators for the Peanut task. To learn LOC# subjects need at most an *M*-capacity of $e + 3$: one *M*-unit for each of the 2 schemes that constitute LOC-and-SerLIN, and another for an operative-learning scheme that can coordinate the two schemes and bind them together into the superordinate operative scheme LOC#. Learning of scheme LOC## would require one more scheme (i.e., #pea) to be chunked, and consequently subjects should need an *M*-capacity of at most $e + 4$ to directly acquire a scheme LOC## equivalent to the entire Formula (6). Given a suitable amount of external support (mentoring, guidance, external mediation), however, the acquisition might take less *M*-capacity, because constituent schemes might then be chunked progressively one after the other. Indeed, if linguistic encoding within diverse visual/haptic contexts has been well practiced, the *M*-demand of acquiring LOC# would be just $e + 2$, and that of acquiring LOC## be at most $e + 3$. An *M*-capacity of $e + 2$ is first accessible to 5- and 6-year-olds, and a capacity of $e + 3$ is accessible only at 7 or 8 years of age.

In tasks where the mode of processing is auditory, verbal mediation could be acquired still earlier, because human-mediated practice of oral language should lead to early acquisition of LOC#, and a visual object-frame scheme (such as #pea) is not needed when the input is auditory. An *M*-demand of $e + 2$, normally found in 5- and 6-year-olds (or even of $e + 1$—found in 4-year-olds) might suffice within the auditory mode for verbal mediation. More detailed discussion of the difference between visual and auditory verbal mediation can be found in Morra (2000).

Task analysis of the Peanut task takes a form analogous to that of Formulas (3), (4), and (5). But now, because the situation is more misleading, the executive demand is greater, and—according to rule (D4)—approximately one scheme can be retrieved from the field of decay using its activation weight *W*. One scheme should easily be retrieved from the field of decay, because the visual frame #pea of the Peanut figure provides cues for this retrieval. The corresponding formulas are

(3*) 6-year-olds: $\mathrm{M}[\mathrm{LOC}^{L1}(\{\#\mathrm{SerLIN}\}_{T,L1}, \{\#\mathrm{pea}\}_{LC}, \{\mathrm{d}_1\}_W, \mathrm{d}_2)]$
(4*) 8-year-olds: $\mathrm{M}[\mathrm{LOC}^{L1}(\{\#\mathrm{SerLIN}, \#\mathrm{pea}\}_{T,L1}, \mathrm{d}_1, \{\mathrm{d}_2\}_W, \mathrm{d}_3)]$
(5*) 10-year-olds: $\mathrm{M}[\mathrm{LOC}^{L1}(\{\#\mathrm{SerLIN}, \#\mathrm{pea}\}_{T,L1}, \mathrm{d}_1, \mathrm{d}_2, \{\mathrm{d}_3\}_W, \mathrm{d}_4)]$

Notice that in Formula (3*) I assume that subjects have already acquired the verbal-mediation *L*-structure LOC#, and that the scheme #pea does not require *M*-capacity because it is boosted by an automatized content (*LC*) structure created in the child by the introductory training with Peanut material provided by the experimenter. Notice further that in Formulas (4*) and (5*) the verbal mediation scheme LOC## is used. Finally, in all formulas, schemes corresponding to *dot*-marked parts to be remembered are labeled d_1, d_2, etc., and one of them

is in the field of decay (i.e., outside *M*-space), boosted by its activation weight *W* and still retrievable when needed, as suggested by Rule (D4).

Perhaps the verbal-mediation operators symbolized in Formulas (3*), (4*), and (5*) can be regarded as a constructivist model for Baddeley's phonological loop. Formula (3*) contains the scheme of Formula (6), that is, LOC#, whereas the other formulas contain a more developed verbal mediation scheme (i.e., LOC##). This difference implies that for verbal mediation to be possible with 6-year-olds, a careful introductory practice with the Peanut frame is needed prior to the task.

SPATIAL AND ARTICULATORY SUPPRESSION IN THE TWO TASKS

(f5) Kemps et al. found that spatial suppression impaired performance on both tasks and in all four age groups. This suppression effect is easily understood as *interference*—as this term has been defined by behaviorists and learning researchers. As research on interference during the 1950s, 1960s, and 1970s has made clear, interference between two local informational processes (cognitive schemes, behaviorist or connectionist alternative associations, etc.) increases with the similarity between (i.e., *with the number of schemes/features shared by*) the processes or schemes in question. Kinsbourne (1980) introduced the concept of "functional cerebral distance" (where distance is defined by neural connections) to explain, among others, the gradient of interference (or of collaboration) found between different content domains or modes of processing: The further away from each other two informational processes are located in the brain, the smaller their mutual interference will be. This valuable heuristic rule relates to similarity as I defined it above (i.e., schemes/features shared) in that psychological information in the cortex is distributed topographically in terms of its semantics. Thus, the more two processes share semantic features, the closer they tend to be topographically in their cortical representation (Pascual-Leone, 1995). Interference is often found in cognitive processes because performance is *overdetermined* by all schemes/processes currently activated in the brain[5]; consequently, competition among mutually incompatible active schemes appears locally as interference. The theory of constructive operators recognized this competitive/overdetermined characteristic of human processing very early (Pascual-Leone, 1969, 1980, 1987, 1989), and as a result it pioneered recognition of central inhibitory processes (the theory of constructive operators' interrupt operator of mental attention) and proposed the analysis of tasks as facilitating versus misleading, and also studied individual differences with reference to proneness to contextual interference (field dependence/independence). We rec-

[5] This is the principle of schematic overdetermination of performance (SOP principle of the theory of constructive operators), which can be regarded as both a generalization of Piaget's principle of assimilation and a generalization of the neural/connectionist principles of spreading of activation and summation of activation.

ognize interference as particularly important within content domains (whether within modalities or modes of processing).

There is an aspect of the spatial suppression task that I should discuss. This is the fact that both tasks (e.g., Corsi's and spatial suppression) are concurrently administered; as a consequence, to avoid disruption due to interference in any of the tasks, subjects must allocate some *M*-capacity to both of them—in the spatial suppression task, once it has been automatized after initial practice, this capacity would be one *M*-unit. As a consequence, and relative to the control, Corsi's task administered concurrently with spatial suppression must have an added *M*-demand of one *M*-unit, so that subjects should be able to recall in it one item less than in the control task. Figure 3 of Kemps et al. shows this "prediction" to be on target.

(f6) The last main finding reported by the authors is that articulatory suppression, as implemented in their study, does not disrupt recall on the Corsi block task in any of the age groups.[6] Even assuming that a more complex articulatory suppression task replicates this effect, the result could be explained from the perspective of the theory of constructive operators. This is so because Corsi's task, as argued before, is both visuo-spatial and facilitating, and, furthermore, interference is minimal between the language and visuospatial domains (because they are functionally independent and have a large "functional cerebral distance" between them). The relative mutual functional independence of visuo-spatial and language processes has been often described, and its repeated observation antedates Baddeley's working memory theory. This relative mutual independence has been recognized in the theory of constructive operators from its inception (Pascual-Leone, 1969; Johnson et al., 1989), because it was present in Piaget's work (his "logical"/linguistic versus "infralogical" domains) as well as in neurology. To quote de Ribaupierre and Bailleux (1994, p. 12):

> Pascual-Leone's model not only distinguishes several silent operators, but also different types of schemes . . . according to their (sensorial) modalities and modes. The latter distinction refers to the way information is coded, and is not necessarily tied to particular types of content; modes are defined as infralogical or mereological (retaining spatio/temporal and/or causal properties), logological (generic knowledge), and linguistic. Although this distinction is not made by Baddeley, one could regard the schemes maintained in the two subsystems as differing both in terms of modality and mode: Information maintained in the AL might correspond to the verbal (modality) and linguistic or logological schemes, whereas information stored in the VSSP might constitute visual and mereological schemes.

[6] Notice that the spatial and the verbal suppression used in this study are not equal in complexity. The spatial suppression task requires four different transformations (finger-tapping displacements) that repeat in cycles; in contrast, the verbal suppression merely involves the repetition of one "transformation" (the verbal utterance "the"). This difference in complexity makes difficult the comparison of these two suppression effects. A verbal suppression that is of equal difficulty would be the cyclic repetition of "one, two, three, four."

CONTRASTING BADDELEY'S WITH PASCUAL-LEONE'S CONSTRUAL OF WORKING MEMORY

Baddeley defines working memory as constituted by a theoretical trinity: a central executive unit, a linguistic component or articulatory/phonological loop (AL), and a spatial component or visuo-spatial sketchpad (VSSP). I define working memory, in a more traditional manner, as the set of all schemes in the subject's repertoire that are hyperactivated at a given time—that is, maximally activated and ready to control performance, processing, or conceptual learning. For me, working memory is not made up by all activated schemes ("the field of activation"), but only those that are hyperactivated. Further, working memory is not just the "field of mental attention" or *M*-space, that is, the set of schemes that at a given moment are boosted to hyperactivation by mental attention (*M*-operator); it is rather all hyperactivated schemes, whether their hyperactivation was caused by mental attention or by other organismic factors such as automatization (i.e., content/experiential learning or *LC*-operator), emotions, and Gestaltist situational saliences. Baddeley's definition makes working memory into a causal triune mechanism that conflates two local modes/domains of processing (linguistic and visuo-spatial) with the central executive functions and with the mental attentional capacities. My definition treats working memory instead as a descriptive construct that emerges by way of the collaboration of different causal organismic factors, among which is the mental-attention mechanism so important in the context of misleading situations. This mental attention, driven by executive schemes, produces both hyperactivation of task-relevant schemes (*M*-operator) and central inhibition of task-irrelevant schemes (attentional interruption), and both these processes help to configure the actual working memory at a given time.

It is as if Baddeley's triune construction were deconstructed in terms of organismic hardware operators working together with different modes and modalities of schemes (among others the linguistic, the visuo-spatial, and the executive schemes). In this deconstruction, Baddeley's central executive is explicated in terms of the dynamic interactions taking place between two diversified collections of processes: a repertoire of task executive schemes of all sorts *and* a functional/dynamic system of four "hardware" or "software" operators—that is, attentional capacities and attentional executive schemes (Pascual-Leone, 1987, 1996; Pascual-Leone & Baillargeon, 1994). These attentional operators are (1) a set *E* of attentional executive schemes, a special kind of control executives; (2) a mental-arousal or "mental energy" capacity (the *M*-operator); (3) an active attentional inhibition mechanism (the *interrupt* operator); and (4) an attentional "closure" mechanism that synthesizes the "beam of attention," that is, the organismic core mechanism of what Gestalt psychologists and Piaget have called internal or autochthonous "field" processes (e.g., "Minimum Principle" of perception, "S-R compatibility" of performance). The two "slave systems" of Baddeley, the visuo-spatial and the linguistic components, would then corre-

spond to specialized and well-learned schematic structures (*L*-structures). These special-purpose *L*-structures are generated by the mental attentional processes, together with other specialized modes of processing (e.g., the *S*-operator, the *T*-operator, *L*-learning operators, verbal mediation), as a result of *human-mediated* experience.

An advantage of this deconstruction is to help explain how and why central-control mechanisms (such as mental-attention or working-memory resources) can also be applied to other modes of processing such as the motor domain (human performance), the logico-mathematical domain, purely mental problem solving, affective processes and emotions, self-development, social cognition, and temporal-structuring processes (e.g., music, rhythms).

CONCLUDING THOUGHTS

In this *Reflections* paper I have argued that the theory of constructive operators can explain all results reported by the lead article, and do so in a manner arguably more analytical than working memory theory. To the extent that my theoretical analyses were successful, one might conclude that theory of constructive operators is empirically complementary with working memory theory because, as Kemps et al. have indicated, developmental patterns and individual-difference data in working memory theory tasks—which working memory theory cannot properly explain—are explained in a refined manner with the theory of constructive operators. The converse, however, is not true; theory of constructive operators explains all its data without need of working memory theory. In an epistemological (dialectical) sense, the two theories are not complementary, even though superficially they seem mutually contradictory—this contradiction is shown in their different formal definitions of working memory. Nonetheless, they are not dialectically complementary because they are not jointly needed to explain the data (this violates Condition C2 of dialectical complementarity, discussed early in this paper) and also because each theory does not control/modify/complete the other, since use of the theory of constructive operators does not necessitate the use of working memory theory (this violates C3). To follow Lakatos' (1980) epistemological ideas, it would seem that theory of constructive operators has greater scope, and more theoretical precision, than working memory theory. The research program of Baddeley's school is very rich empirically, and yet its theoretical model is not complementary with, but rather can be subsumed under, the theory of constructive operators. This is not to say that as a theory Baddeley's is not an important alternative for developmental psychology. Theories are working tools, and psychologists will always choose those that they prefer and find more intuitive. Baddeley's is an alternative to Pascual-Leone's theory without complementing it.

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Received January 26, 2000; revised July 6, 2000