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Integrating Neuroscience and Cognitive Science. Methodological aspects

Renzo Beltrame

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Integrating neuroscience and cognitive science. Methodological aspects[1]

Renzo Beltrame[2]

The integration of the knowledge that was developed by neuroscience and by cognitive science involves both technical and methodological problems. This paper mainly deals with methodological aspects, since the technical aspects would entail focusing on a single, well-delimited problems. However, some preliminary choices are needed to delimit the discussion.

Integration concerns biological systems that we consider as being able to do mental activity, and a first choice regards how to study the facts under discussion. We decide that the facts investigated and the procedure employed to study them must be repeatable without any restrictions on principles or methods. We do not discuss here whether this requirement alone can define the scientific method; we only observe that it ensures the unlimited possibility of proving or disproving a fact, which is a frequently cited feature of scientific method[3]. Furthermore, this repeatability requirement will prove to be a very strong methodological choice, whose consequences have a very sharp effect in delimiting the discussion[4]. The repeatability proposed here is a mental attitude, a way of considering the facts, although the consequences deeply affect the subsequent way of operating. In each experiment, for instance, we can have only one dependent variable, and we must study its dependence on only one independent variable. Then we must assign a constant value to all the other variables that we think may influence the experiments. These conditions are all necessary to have repeatable experiments. In mathematics, where we have to deal with mental facts and their relations and where demonstrations take the role of experiments in physics, we use explicit definitions to code pieces of reasoning and we introduce symbols and the rules of their combination. Then strings become suites of physical objects - pictures, drawings - and the demonstration becomes equivalent to a sequence of string rewriting that starts from the initial string

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A very preliminary report on this subject appeared in December 1996 as CNUCE Report C96-31. It will appear in the book *Scritti in memoria di Silvio Ceccato*.

2. National Research Council of Italy - Pisa. *Email*: renzo.beltrame@cnuce.cnr.it

3. I think here of Popper's falsification thesis. See K.R. Popper, *The logic of scientific discovery*, 1934, 1959.

4. This point was discussed in R. Beltrame, "On brain and mind", *Methodologia*, 10 (1992), pp. 7-13.

and reaches the thesis string by using the specific hypotheses and the theorems that were previously demonstrated: that is, the equivalence of certain strings. The rewriting operation is a physical process by which one or more physical objects replace another physical object, and the possibility to perform arithmetic on machines - both the old mechanical ones, and the current electronic computers - follows from this point of view[5].

We emphasize that the repeatability requirement is incompatible with a statement of complete freedom of the individuals we are studying; at least when we interpret this freedom as the impossibility to test every statement about the individuals' behavior by using repeatable experiments. Because such an impossibility also implies the impossibility of having a scientific theory of the individual's behavior, we usually introduce a suitable set of parameters that characterize in a repeatable way the state of the individual we are studying[6]. The repeatability requirement is also a very useful constraint, because it originates a set of facts that were repeatedly checked, and that we can recheck at any moment.

A second choice concerns the characteristics of the mental facts and activities. We require the definition of the mental facts and activities to be compatible with the possibility to consider them as being private facts. This requirement preserves a property that our culture assigns to mental facts and activities. We usually think of this character as being a consequence of an ontological status, and we will come back to this point later in the paper. For now the reader can accept as a safe hypothesis that this character follows from a deliberate choice in defining mental facts and activities.

In this paper we will assume that mental facts and activities are defined by an injective function into a subset of the physical processes that occur in the system that we consider is performing the mental activity. This choice and the choice of the terms of this mapping are motivated only by practical reasons, since definitions are neither true nor false, but only less or more useful for certain purposes. In this discussion we will refer to the target of building a theory that will explain and predict the behavior of the systems we are studying. If we plan to integrate neuroscience and cognitive science, we must then define mental facts or activities in such a way that these definitions will be compatible with the physical description of the system behavior, and they shall be useful to explain and predict the behavior as psychology studies it, and, for humans, anthropology too. This choice will allow us to decide without any ambiguities when a mental fact or activity occurs, and, as we shall see, it will guarantee repeatable experiments. So, it agrees with our previous choices.

It should become clear that we can freely choose the starting point of our description. We may start from physical things, and define the mental things[7], as we will do in this paper. Then we must complete our description, and so our knowledge system too, by using mental facts and activities to describe physical things and their interactions. We may equally start from mental things and define physical things and their interactions. Then we must complete the description of our knowledge system by using physical things and their interactions to describe mental facts and activities. In this operation we must fulfill the methodological constraints that we discussed above, and that scientific praxis imposes on us. A further consequence of this program is that no hierarchy is introduced a priori, and that we have no need to come back to any type of methaphysics.

By analogy with the dynamics of physical systems, we will call dynamics of mental facts or of mental activities a theory that explains and predicts the occurrence of mental facts or activities. In discussing the dynamics of mental facts and that of physical processes we will use a deterministic point of view to simplify the exposition. If we will use a probabilistic point of view, then we substitute conceptually the occurrence of a fact with a distribution of the facts' occurrence; but the mathematical formalization will become more complicated, and we will introduce many technical hypotheses to have well defined notions.

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5. The recent sophisticated computer programs of symbolic manipulation in algebra or in mathematical analysis are methodologically grounded on this viewpoint.

6. This problem has a long history which we can trace back to Aristotle.

7. I tried to use this point of view in R. Beltrame, "On brain and mind", *cit.*, where mental facts were defined as causes that we introduce to explain the observed behavior. As we shall see below, we have many other possibilities to define mental facts, and the choice of a cause-effect relation raises a certain number of difficulties of which I was not sufficiently aware in that paper.

In the physical description of the systems whose behavior we are interested in here, our reference will be a theory that satisfies the following requirements: the predictions will lead to repeatable experiments, we will systematically use the cause-effect relation instead of a mere correlation between the events, we will fully predict the energy exchanges, and a bijective function will hold between the causes and their effects. We will also refer to a geometrical representation in which the dynamics of a physical system is represented by paths that do not intersect in a phase space of a suitable number of dimensions. These assumptions are difficult to satisfy in practice, due to the mass of information that we must involve, and to the essential nonlinearities of the theory. Nevertheless, very reasonable and sharp methodological assumptions support these choices, and we have a considerably simplified discussion of the integration between the physical description and the description of the psychology. The lines along which mental facts and activities are defined, lead to a dynamics of the mental activity that has a very different representation, and the differences between the two dynamics become immediately evident when we refer to a physical description with the characters indicated above. Clearly we might trace back these differences also when we use a more realistic physical description, for instance a description that follows the approach of statistical mechanics. Nonetheless, statistical mechanics would require a presentation that is more cumbersome, and that would mask essential differences between the physical and the psychological approach. However, the most underlying reason is that I did not outline these differences with sufficient clarity when, in giving a physical description of the behavior of the biological systems, I tried to follow the approach of statistical mechanics or that of continuum mechanics.

In particular, we will show that the theory of the occurrence of physical facts is not isomorphic with the theory of the occurrence of mental facts. This conclusion follows because the conditions, that we require to hold in physics to apply a cause-effect relation, are not compatible with the analogous conditions that we require to hold in psychology. So, we cannot identify the dynamics of the mental facts and activities with the dynamics of the physical processes that occur in the system that we consider as performing the mental activity, and so we cannot assume a reductionistic position. The most extensive consequences follow however from defining mental facts and activities by using only a part of the physical process that we must introduce to give a satisfactory physical description to our systems behavior. We will show that we can derive from this decision the theoretical possibility that a mental fact or activity will occur again in the same subject, or that it can be identical in different subjects, that is in system that do not have the same evolution. We thus find a strong reason to define mental facts, and the roots of their possible intersubjective character. We will also derive that only correlation can be set between the occurrence of mental facts and activities, and that the correlation has an essential, probabilistic character. So, we will go back to the physical description, if we wish to explain the occurrence of the mental facts and activities by means of a one-to-one relation between the causes and their effects, and this is another strong reason to refuse a reductionistic position. We will show that the occurrence of a mental fact or activity is always accompanied by a further physical activity besides that we used to define the mental fact or activity, and that this further physical activity will depend on the current state of the system which is performing the mental activity. Since the subsequent physical activity shall depend also on this further physical activity, we need again the physical description to predict the flow of the mental activity in a deterministic way. So, in our theory, we must develop both the dynamics of the physical activity, and that of the mental activity.

The requirements that we imposed to the definition of the mental facts and activities are a consequence of our decision to operate in a scientific framework, and this point of view is necessary both in cognitive sciences and in discussing their integration with neuroscience. In integrating neuroscience and cognitive sciences, we have to avoid any ontological dualism between physical and mental things[8]. We shall see that this problem has a rather simple solution when we take into account the dynamics of the mental activity, and particularly the constraints that we usually impose to the development of our knowledge system. The requirement shall be determinant to have a knowledge system which is free of contradictions in the part that we use to perform logical deductions. After having introduced as constraint that someone is the subject of an activity which transform another thing, we cannot ascribe this

8. This is a way to formulate the old problem of the dichotomy between the mind and body, or, more recently, the dichotomy between the brain and mind.

activity and its consequences to another subject, neither to the person who is performing the mental activity of thinking that someone is performing that transformation activity, otherwise we contradict ourselves. Since we use logical deduction to obtain predictions that concern our practical activity, and particularly relations of our body with other physical bodies, and since from a contradiction we can deduce both a statement and its negation, we will avoid contradictions.

We will mention in advance another point, which concerns mental activity, and which is particularly evident in mental categorization. As we will discuss later, when something is mentally categorized in a certain way, this fact is frequently presented as a further property of the thing thus categorized. In this paper we must frequently deal with the mental activity by which we obtain the categorization, and with the conditions of its occurrence. This situation happens, for instance, when we consider something as being a cause, effect, stimulus, response, or organ; but it also occurs when we consider a system as being intelligent, living, or free. As a rule we will explicitly declare when we are dealing with mental activity. In the other cases mental activity occurs, but we are only concerned with its results, or with its consequences, and we will not mention it explicitly, in order not to affect the readability of the paper.

Finally we will assume as implicit hypotheses that those mathematical properties hold that are necessary for the elements involved in our discussion to be well defined.

How to define mental facts and activities

When we discuss the integration between neuroscience and cognitive sciences, we are concerned with the problems that we meet when we define mental facts and activities[9]. The definition of mental facts starting from physical facts requires a certain number of specifications[10] because we inherit a certain number of methodological problems from the philosophical tradition. The ontological dualism and the various kinds of reductionism are significant examples of these kinds of problems. For these reasons I thus consider it safe to discuss briefly a certain number of critical issues that arise when we use the particular class of physical things involved in neuroscience to define mental facts and activities.

We recall that we decided that the following two conditions must hold in our discussion:

- the investigated facts, and the procedure employed to study the facts must be repeatable without any restriction on principle or method;
- mental facts and activities must be defined in a way that is compatible with the possibility to consider them as having a private character.

The second constraint prevents us from identifying mental facts and activities with physical facts or processes occurring in the biological systems that we assume as performing mental activity.

However, the occurrence of things with a private character cannot be observed in a repeatable way, because the observation involves someone's account, description or testimony as a constitutive element: in our case the subject who is thought to perform the mental activity. So, when we decide to satisfy the repeatability requirement in studying humans, the accounts, descriptions, or testimonies of the persons, who we think as performing the mental activity, to identify the mental facts. For the same reason we cannot use the testimony of the observer cannot be constitutive in the experiments[11]. In scientific experiments only the physical facts that concern the body of the person that we assume as performing mental activity, or the physical transformations that he performs on other objects can thus be the dependent variable, or the independent variable, or one of the parameters that characterize a scientific experiment. Psychological and mental facts cannot have this role. Accounts, descriptions, and testimonies can only serve as indications to get back directly to the fact that we want to assume either as the

9. This point was discussed with more detail, and following the viewpoint of this paper, in R.Beltrame, "Methodological aspects of the mental facts definition, and of their dynamics", in Aa.Vv., *Categories, Time and Language*, Quaderni di *Methodologia* 5, Roma 1998, pp. 45-100; and in a previous version as CNUCE Report C97-25, 1997 (both in Italian). We will summarize here the main points that are necessary for our discussion.

10. Analogous specifications are necessary when we have to define physical facts starting from mental facts.

11. If the subject testimony is constitutive, then we could not compare the results of experiments carried out on different subjects, and we should find the same limit if the testimony of the experimenter were constitutive.

dependent variable, or as the independent variable, or as one of the parameters that characterize the experiment. Although these constraints directly concern the experiments, they also affect the theories, because in scientific activity a theory must give predictions that can be tested by means of scientific experiments. At the end, if we consider the repeatability requirement as being a character of the scientific method, then we must define mental facts and activities by means of physical facts before introducing them in any scientific context.

Both the constraints stated above are satisfied when we assume that mental facts are defined through a mapping into physical things, and in the following of the discussion we will assume that definitions use physical processes which occur in the physical system that we assume to be performing mental activity. This way of defining mental facts and activities is clearly compatible with the requirement that mental facts and activities can be considered as having a private character, because we do not identify them with physical facts, but we have only a mapping into the physical facts. Furthermore it allows us to communicate the definitions to other people. We further characterize the mapping which defines the mental facts and activities in the following way. We decide that a mental fact or activity occurs every time the physical process occurs that we used for its definition. We also decide that, whenever we predict the occurrence of a mental fact or activity, we also predict the occurrence of the physical process that we used to define it. Finally, when the physical process does not occur, which we used to define a mental fact or activity, we decide that the related mental fact or activity did not occur either. In this way we can assert without ambiguity whether a mental fact occurs, and we can test its occurrence by means of repeatable experiments on the systems that we plan to use in the experiments. Clearly, hypothetical physical facts are not allowed in the definitions, and we cannot substitute a physical process with a mental category or more generally with another mental fact or activity, because we would really like to define a mental thing by means of other mental things[13]. We give thus an unsatisfactory definition when, for instance, we use a physical fact which is described only as a change of state[14]. The substitution of a physical fact with a mental fact is acceptable only when it is clear from the context which physical process the mental fact or activity refers to; but in this condition the substitution simply becomes a linguistic shortcut of no theoretical interest.

In mathematics it is usual to characterize the mapping that we proposed to use for defining mental facts, as an injective function $f: (M \rightarrow P)$, of the set M of the mental facts and activities we have to define, into a subset P of the physical facts that occur in the systems we plan to use in the experiments. As we shall see below, we will not require f to be also surjective, then it is only left invertible[15].

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12. Mathematics seems to disprove this statement, because the interpretation of the symbols leads to mental categories, with the exception of some applications to physics in which physical quantities are involved. Nevertheless it is possible to confine the interpretation of symbols to the beginning and to the end of a procedure or of a theorem demonstration. In this way demonstration can be thought of as a sequence of rewriting operations on the expressions that describe the hypotheses, in which the rewriting rules are of a general type, that is metamathematical, or they follow from the stated definitions, or they follow from previous theorems.

13. This observation also holds when we consider more general levels of a theory. At these levels of a theory we must use mental categories to obtain the required generality, but, if we wish to start from one of these levels and to use a top-down approach, then we must develop the theory and introduce the necessary definitions until we reach the level of specificity that ensures the link with repeatable experiments.

14. This point was not sufficiently emphasized in my past papers. For instance, in R. Beltrame, "La première machine sémantique", *4me Congres International de Cybernetique*, Namur, 1964; R. Beltrame, "L'analisi in operazioni", *Nuovo 75*, 1 (1967), pp. 17-21 (in Italian); R. Beltrame, Osservazione e descrizione meccaniche, in *Corso di Linguistica Operativa*, S. Ceccato Ed., Milano, 1969, pp. 115-139 (in Italian); R. Beltrame, "Perceptive Operations", *Thought and Language in operations*, I, 2 (1970), pp. 174-198.

15. We recall some mathematical definitions that we use here. A map is defined by a triple (G, X, Y) where X and Y are sets, and $G \subseteq X \times Y$; the set G is said to be the graph of the map. A map will be called a function when it is single-valued: that is, when it assigns to each element $x \in X$ exactly one element $y \in Y$ such that $(x, y) \in G$. The functions will be notated $f:(X \rightarrow Y)$ and $y = f(x)$. The set X is called the domain of the function f, and the subset $f(X) \subseteq Y$ its range. When $x \neq y$ implies $f(x) \neq f(y)$ the function is said to be injective. When $f(X) = Y$ the function is said to be surjective (onto). A function is said to be bijective when it is both injective and surjective. A function f is said to be left invertible when there exists a function $g : (Y \rightarrow X)$ such that gf is the identity function on the set X. A function f is said to be right invertible when there exists a function $g : (Y \rightarrow X)$ such that fg is the identity function on the set Y, and a function is said to be invertible when it is both left invertible and right invertible; we can prove that an injective function is left invertible, and that a bijective function is invertible.

When we give a physical description of the systems that we think of as being able to perform mental activity, we introduce a certain number of facts, for instance a certain number of processes, which are necessary to develop the dynamics of the physical activity of these systems. Since we assumed that mental facts are defined through an injective function into physical processes, we have to decide whether all the physical processes that we introduced in the physical description of the system behavior are used in defining mental facts. The alternative of using all these physical processes seems methodologically the simplest one, but we can immediately observe that it would lead us to defining more mental facts than those we use in our cultures. Furthermore, we will show that mental facts so defined cannot occur again during the life of the same subject. We simply expound this statement because we must first discuss the characters of an optimal physical theory of our system behavior before proving this statement.

We thus assume that some physical processes are not used to define mental facts or activities, although they are necessary for a physical description of our system dynamics. Formally this choice means that the injective function into physical processes, which we will use in defining mental facts or activities, is not surjective, and thus it is not a bijection. Furthermore, we will see that we will obtain a dynamics of the mental facts in which the occurrence of a mental fact cannot be predicted by the occurrence of mental facts only. When we decide to define mental facts by using only part of the physical processes that are necessary to describe the physical behavior of our systems, we must decide which physical processes we will use to define mental things. This problem is solved best when we are dealing with a specific situation. However some general remarks are possible. If we exclude the physical processes that are necessary to ensure the stability of the biological system[16], then we are not forced to accept that mental activity occurs continuously. Mental facts and activities shall be defined by using other physical processes, and these physical processes usually have environment actions as direct or indirect causes. In developing a physical description of the behavior of a biological system we can find that different processes can ensure the stability of the system: that is, the system can be stable in a range of values of the observables. In these cases we can also use changes in the value of these observables to define mental facts and activities: for instance, quantitative changes in metabolic activity, or in molecule exchanges between groups of cells and their intracellular space[17].

In our discussion we spoke of defining mental facts or activities by using physical processes, but we might decide to define mental states through a mapping of physical states onto mental states. If necessary, this mapping must satisfy the same properties as the analogous mapping that we proposed for defining mental facts or activities; that is we require that an injective function holds of the mental into the physical states, and that the same one-to-one function holds between their occurrence. However, we will consider as a particular type of process the situation in which the values of the observables that characterize the process do not change during a certain interval of time. Furthermore, we will not use a state of the system as a cause, but the process that brought the system to that state. With these assumptions, we will only use processes as causes in our theory.

The conditions that we stated above for defining mental facts become unnecessary to define a mental fact by using a relation with a physical fact like, for instance, a cause-effect, a stimulus-response, or a semantic relation. If we use the occurrence of the physical fact that is one of the terms of the relation to define the occurrence of the mental fact, then the relation is not necessary, and we can use a mapping into a physical thing with the properties stated above. Instead, if we use a physical fact that can be considered as being in the stated relation with a certain other physical fact for defining a mental fact, then this physical fact must be unique, otherwise the mental fact is ambiguously defined. However, in this case too, the relation is not necessary, because we can define the mental fact by mapping it directly into this last physical fact[18]. In the following of the paper we will avoid to consider this way of defining mental things, because it may add the properties and the consequences of the particular relation to the

16. By stability of our biological systems we mean here that the system maintains the behavior for which we are interested in studying it.

17. When we mention the use of physical processes to define mental facts and activities, we shall think of the physical processes as having this wide meaning, and this meaning is in good agreement with the viewpoint of physics, where changes in the value of some observable are a way of defining a physical process.

18. This point was not sufficiently stressed in R. Beltrame, "On brain and mind", *cit.*

simple individuation that we require to a definition. This misleading possibility is immediately evident if we think of the cause-effect relation in a framework where no isomorphism holds between the dynamics of mental and physical facts. In our discussion we will thus assume that mental facts and activities are defined through an injective mapping into physical processes with the properties stated above.

In developing a theory of the behavior of the systems that we consider as being able to perform mental activity, we must think of these systems as being able also to define mental facts. The theory must thus contain the description of how they define new mental facts, and the dynamics of this activity. The bases of this activity have a more simple presentation in terms of mental activity. We will thus briefly discuss which relation we will set between mental facts and mental activity.

Mental facts and mental activity

Until now we used the two phrases 'mental facts' and 'mental activity' without specifying how they may differ. Here we will briefly point out which differences we are going to give to them. The two forms reflect two main schemes that historically were followed to think about mental things. The more common scheme thinks of mental things as entities, and the word 'mind' designates the collection of these entities. When we study the occurrence of these entities, a specific activity becomes necessary to speak properly of their occurrence. Usually this activity is not clearly defined: it is simply ascribed, as a faculty, to the subjects that we consider as being able to perform mental activity. The other scheme conceives mental things as activities. The word 'mind' then designates the subject of these activities, the activities are qualified as being 'mental', and they are thought as being constitutive of mental facts.

When we use the first scheme to define mental things, we have a more direct connection with culture: that is, with the set of elements that are transmitted to individuals by the group in which they live. We are however at a disadvantage in building a theory with a satisfactory degree of generality, because the choice of mental facts depends on the influence of a particular cultural context. So, when we develop a theory, the possibilities of the biological architecture may be easily masked by the habits that are active at a particular historical moment in the group we are studying. These habits must be considered as variables in the theory, because they explain and predict some behavior differences between individuals, and between different moments in an individual's life.

However, the most negative effect of using the first scheme concerns the difficulties of introducing new mental facts into the theory of our systems' behavior. The learning activity is a continuous source of new mental facts. Linguistic communication, both spoken and written, is another source. If mental facts are assumed to be atomic, then we can introduce new mental facts into the theory of the system's behavior only by new definitions, and a theory becomes unmanageable in which we have frequent changes in the definitions. We can get round this difficulty by developing a theory in which mental facts can be composed of a limited number of other mental facts. However, we know from psychological atomism that a mental fact can only exceptionally be decomposed into a sequence of more simple ones. The rule is a decomposition into more simple mental facts and their relations. The problems arise in defining these relations by an injective function into physical things whose occurrence can be observed, following the requirements of the scientific praxis, on the system that we assume to be performing the mental fact. In particular, we must be aware that these relations can often be a by-product of the decomposition criteria: that is, they are part of the mental activity of the observer only, and we cannot consider them as being part of the mental activity of the observed system. In this case it is a contradiction to plan a suitable mapping into physical things that satisfy the criteria stated above.

For these reasons I prefer the more radical alternative of using the second scheme discussed above. That is, I prefer to define mental activities by an injective function into physical processes that occur in the system which we consider as performing mental activity. In this way we can think of mental facts as clusters of activity, and this activity becomes constitutive of mental facts. Mental facts can now be different in different individuals, and they can have a different stability in the same individuals through their life, for as long as learning concerns mental facts that do not require the introduction of new characters for the mental activity, we do not have to change our definitions in the theory[19]. In the theory we have to define a mental activity with a suitable number of characteristics so that the theory will explain and predict at what time the mental activity previously defined shall occur. The theory must also contain the rules of clustering the mental activity by which the mental facts originate, but this problem does not concern the definition of mental activity, it only concerns the definition of mental facts: that is, the dynamics of mental activity. Furthermore, the definition of mental activity is facilitated because we now have to map an activity onto another activity. Unfortunately, the development of the theory is not equally facilitated, since, as we shall see below, no isomorphism holds between the physical and the psychological theory of the systems' behavior. The rules that describe which physical process shall follow another physical process do not usually map onto the analogous rules that concern the mental activity, and this mapping is limited to very particular situations. Thus no reductionism is possible.

Recall that the point of view discussed here is typical of a person who analyzes the constitutive mental activity, and that the subjects who perform mental activity usually assume a different point of view. Typically, these subjects are only slightly interested, if at all, in the constitutive activity, and they are mainly concerned with relations among the things that the analyst considers as being results of constitutive activity. Recall that our languages have an equal possibility to emphasize a relation among things, or the mental activity by which someone sets a relation among things. We can say, for instance, 'the cat was near the door', or 'I saw the cat near the door', or 'I think that the cat was near the door', and so on. When we describe the mental activity we have thus a mental activity which is instrumental, and a mental activity which is the object of what we are dealing with. However, this only means that we also have to define the mental activity by which we consider a thing as being a mental thing, and we have no *regressum ad infinitum* in the psychological description.

In this paper we will refer to the way of defining mental things that we have presented above because it is useful in discussing the integration of the knowledge that was developed by neuroscience with the knowledge that was developed by cognitive science. However, other ways of defining mental things are possible, and even more suitable for different purposes.

Finally, note that the definitions both of mental activities and of mental facts, do not contain the conditions of the occurrence of the defined things. This aspect of the problem (i.e., the dynamics of mental things) will be the main topic of the last section.

Main characters of the integration

Following the general choices outlined at the beginning of this paper, we are led to define mental things by means of an injective function into physical things. We recall that the introduction of physical things is required by the repeatability constraint which is required by scientific praxis. The necessity of a relation, rather than an identification, follows from the further constraint that the definition of mental things be compatible with the possibility to consider them as having a private character, and the same injective function must subsist, by our decision, between the occurrence of a mental thing and the occurrence of the physical thing we used to define it. The physical things must thus be chosen from the physical changes or processes that we observe on the systems that we consider as performing mental activity. The integration between neuroscience and cognitive sciences then becomes the integration of two dynamics: the dynamics of mental facts or activities, and the dynamics of the physical facts that we used to define them. By dynamics we mean a theory that explains and predicts the occurrence of facts: that is a theory of the occurrence of facts.

Since the dynamics of the physical activity must not concern things having a private character, we cannot mix mental and physical things within the same dynamics. We can employ the designation of one order of things to indicate the other, by making use of the injective relation that we used for the definitions. We must be however aware that the exchange concerns only the names, and not the things.

[19]. This strategy was followed by the Italian Operative School in developing a model of mental activity, A good description of this model can be found in S. Ceccato, "A Model of the Mind", in E. Caianiello Ed., *Cybernetics of Neural Processes*, Quaderni della Ricerca Scientifica, CNR Roma, 1965, pp. 21-79. A clear sketch of the history of the Italian Operative School can be found in V. Somenzi, "The Italian operative school", *Methodologia*, 1, 1987, pp. 59-66.

Since we introduced an injective function to define mental things, we can investigate whether an isomorphism holds between the two dynamics. Unfortunately no global isomorphism holds between the two dynamics, firstly because in physics and in psychology conditions were historically established to apply the cause-effect relation, which are not compatible.

The physics inherits from elementary classical mechanics the use of a mental scheme in which the cause of a body movement is external to the body itself; so we cannot assume a mechanical body as causing its movement. We must consider this assumption to be part of the mechanical body definition when we are dealing with the dynamics, and we find it explicitly stated in Euler's *Mechanica*[20]. Instead in psychology we use a mental scheme in which we think that animals and humans may cause their behavior, and in particular their mental activity. Thus in psychology we can think of the subject as being the cause both of mental activities, and of the physical changes in themselves and in their environment.

No methodological reason forces us to assume that the constitutive mental activity of the cause-effect relation is different in physics and in psychology. So, we assume the constitutive mental activity of the cause-effect relation to be the same, and the lack of an isomorphism between the dynamics of physical and mental activity does not affect this assumption. We will make this assumption for all mental categories and categorization schemes, because it simplifies the definition of general notions, like cause and effect, although we have to test experimentally the occurrence of the same activity in different contexts: that is, the occurrence, in different contexts, of the physical processes that we used to define the mental categories and the categorization schemes. Therefore, when we maintain this assumption we have to assume that different conditions must hold in physics and in psychology to consider as being correct the choice of the things that we consider as being related as cause and effect.

When we view animals and humans as biological systems, we describe them and their behavior with the schemes of physics[21], and we automatically introduce the assumptions that are implicit in these schemes. We cannot thus maintain in this kind of description the scheme of psychology, because we would have to introduce the subject as the cause of physical processes that modify itself, and this fact will lead us outside physics. Yet we cannot base a psychological description of animal and human behavior on the schemes of physics. In these schemes every change has its cause in something that is different from the thing that is changing. Then we lose the subject as it is thought of in psychology and its autonomy, whose consequences are today an essential character of the psychological description of human behavior. When we are concerned with the definition of mental facts or activities, the repeatability constraint forces us to have only a mapping of mental things into physical things. However, we also want to predict the occurrence of mental activity, and we want to test the predictions by means of repeatable experiments. We cannot thus assume that the subject who is behaving as being the cause of the predicted behavior, because we lose the repeatability of the experiments when we conceive of the subject as a particular individual at an instant of time. Nevertheless, the two schemes are both acceptable and useful. We can use them together, but we must be aware that we cannot freely transfer our deductions from one scheme to the other, and that we cannot claim that all the deductions of the two schemes hold together. Without this awareness we may introduce contradictions, and biology offers examples of this misleading possibility, for instance with bacterial chemotaxis.

Motile bacteria will swim toward higher concentrations of certain chemical substances that we know from the theory and the experiments will increase their life expectation (favorable chemicals), and they swim away from higher concentrations of chemical substances that we know will reduce their life

20. In Newton's formulation: "Corpus omne perseverare in statu suo quiescendi vel movendi uniformiter in directu, nisi quatenus a viribus impressis cogitur statum illum mutare.", it is not sure whether the cause of a mechanical change must be external to the physical body. No doubt it is possible with regard to Euler's formulation: "Corpus absolute quiesciens perpetuo in quiete perseverare debet, nisi a causa externa ad motum sollicitetur." [L. Euler, *Mechanica sive motus scientia analytice exposita*, 1736, Ed. P. Stäckel. Leipzig, 1922, Vol. I, p. 27]. Feynman makes the same assumption by stating "that the force is equal to zero unless some physical body is present" [R.P. Feynman, R.B. Leighton, M. Sands, *The Feynman lectures on Physics*, *cit.*, Vol. I-1, pp.12.1 ff.]. In elementary mechanics we also think of the mechanical body as being atomic and not composed of parts; and this character too must be considered part of the definition of mechanical body. In fact a single scalar and a direction, that is a single vector, completely describe the action of the environment on the body. Finally, when we think of the mechanical body as being composed of parts, this viewpoint is applied to the single parts of a body which we consider as being atomic (that is, the parts that we decided not to split again).

21. Biochemistry, molecular biology, and electrophysiology are in fact grounded on physics.

expectation (noxious chemicals). Such a behavior is very subtly adapted and we know many details of it in *Escherichia coli (E. coli)*[22]. The bacterium swims by means of flagella. Counterclockwise rotation of the flagella allows all the flagella to draw themselves together into a coherent bundle, and the bacterium swims uniformly in one direction. Clockwise rotation of the flagella causes them to fly apart, the bacterium tumbles chaotically, and its motion has no statistically preferred direction. In the absence of environmental changes the counterclockwise direction of the rotation is reversed every few seconds for a brief interval of time, producing a characteristic pattern of movement in which a straight line is interrupted by abrupt, random changes of direction. Therefore changes can be detected, which may occur in different places of the environment. When swimming at a constant velocity, the spatial gradient of chemical substances is detected as change in the chemical's concentration over time. If the concentration of noxious chemicals increases, then rotation reverses more frequently, thus inducing a more frequent change in the direction of the motion. If the concentration of noxious chemicals decreases, then rotation reverses less frequently, and the bacterium goes away from high concentrations of noxious chemicals. We observe an analogous procedure when the concentration concerns favorable chemicals. If the concentration increases, then rotation reverses less frequently, and the bacterium goes toward regions of higher concentrations of favorable chemicals. If the concentration decreases, then rotation reverses more frequently and the bacterium moves in different direction. In every case the frequency of reversing the rotation never goes to zero. So, even in favorable conditions, the possibility of better conditions is explored.

For this bacterium we have a rather detailed hypothesis to explain the observed behavior in terms of physical processes, starting from a small family of transmembrane proteins whose level of activation increases when they are bound to a noxious chemical, and decreases when they are bound to a favorable chemical. The activation induces a chain of chemical reactions. They involve the concentration of four cytoplasmic proteins, and the multiproteins complex that acts as flagellar motor. The result is a clockwise rotation of the flagella and thus a tumble. The response time is about 200 milliseconds. Many other details of the adaptation process are known, which enables these bacteria to have a very good response. They can detect concentration changes over a range from less than 10^{-10} M to over 10^{-3} M for some favorable chemicals.

Contradictions may arise when we decide to think of a behavior as being intelligent only when we consider the system as causing the occurrence of its behavior because in physics we use a mental scheme in which the cause of a change is a different thing from the changing thing. Therefore, if we decide to consider a behavior as not being intelligent when we think that its occurrence is provoked by a cause external to the system, then we should refuse to consider as being intelligent every behavior whose occurrence we explained in terms of physics. This conclusion will hold for human behavior too; but this very unpleasant conclusion arises out exclusively from our pretension that two incompatible sets of conditions hold together: the conditions that we require to apply the cause-effect relation in physics, and the conditions that we require to apply it in psychology.

We might weaken the opposition between the two viewpoints, and even remove it, by changing one of them, for instance the point of view of psychology. It should however be necessary to reconsider a large part of our culture, which is based on the freedom of the acting subject, and, like ethics and criminal law, derive a statement of personal responsibility from this assumption[23]. This solution thus raises serious practical problems. We prefer to maintain two different theories of the behavior for the systems that we consider as being able to perform mental activity: a physical, and a psychological theory. When we decide to integrate these two theories, we have as a necessary link only the injective function between physical and mental things that we used to define mental things. As we saw in the previous sec-

22. See B. Alberts, D. Bray, J. Lewis, M. Raff, K. Roberts and J.D. Watson, *Molecular biology of the Cell*, 3rd Edition, Garland, New York, 1994, pp. 773-778, and the related bibliography.

23. The tendency to consider human behavior as being strongly dependent on external conditioning arose during quite recent criminal trials in Italy. The problem was recently discussed during a recent conference in Washington, *Neuroscience and the Human Spirit* sponsored by the Ethics and Public Policy Center, Washington DC, 24-25 Sept. 1998; see also "Does neuroscience threaten human values?", *Nature Neuroscience*, 1, 7 (1998), pp. 535-536. Another related viewpoint is the distinction between the faculty of understanding and the faculty of will in discussing whether the persons are in full possession of their faculties. Finally, this point is also related to the discussion given below on the paradigms used in performing mental activity.

tion, we assume that mental things are defined by using only part of the physical processes that are necessary to describe our system's dynamics. This decision has strong consequences on the integration of the physical description with the psychological description of our system's behavior, but, before discussing these consequences, we will briefly review the characteristics of a physical description that we consider as being optimal.This discussion will offer further reasons to assert that no global isomorphism holds between the two theories, nor to a large extent between the descriptions either, that use these two different models. So, we must also clarify their mutual relations.

Optimal characteristics of a physical description

We recall that in physics we use a mental scheme in which the cause of a mechanical body movement is external to the body itself, and mechanics is an essential part of fundamental physics. Furthermore, the actions of a mechanical body on another mechanical body are thought of as physical processes, and thus they imply a change in the agent too. The causes of these processes must be external to the agent, to agree with the assumption stated above. So, the action of a mechanical body on another mechanical body is conceived of as an interaction, and when the interaction is between two bodies, we must think of the mutual actions as being equal and opposite[24]. When in physics we represent elementary interactions by forces, this decision is equivalent to some strong methodological choices. Since a vector represents mathematically a force, and vectors are defined on linear spaces, we can compose them linearly[25]. When we use a linear law of composition the result has always the same properties as the components, and so we can safely deduce the properties of the result from the properties of the components. Furthermore the components are all independent, because in a linear composition a component which enters with zero weight does not modify the effect of the other components. However, we pay for this very useful property with the constraint that the combining elements must be of the same type. Therefore we cannot propose a linear law of composition when we wish to compose elementary situations of different types, or when we wish to obtain a result whose properties are different from the properties of the components.

In classical non relativistic mechanics vectors are defined on spaces whose model is a three-dimensional Euclidean space. So, we have a finite orthonormal system, which is also a basis, and we have a scalar product from which we can obtain the projections of a vector onto another vector: thus, also the projections of a vector onto the elements of the basis[26]. Furthermore, the displacement too of a mechanical system, which is the final effect of a force, is defined by a vector. The scalar product of a force with the displacement of the point to which the force is applied, gives the value of the energy exchanged by the system as an effect of a displacement when a force is acting on the body.

In physics we further assume that forces, which we use to describe fundamental interactions, are conservative[27]. Furthermore we assume these forces also have no explicit dependence on time[28]. We recall that a force is said to be conservative when its work in moving a mechanical body does not depend on the path along which the physical body is moved, but only on the start and end point of this path. Conservative forces thus induce energy exchanges that do not depend on the particular process, and the quantity of energy exchanged is described by the differences of a scalar function: the potential. Finally, it is possible to prove that, when a force results from composition of conservative forces, it is

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24. The extension of this scheme by linearity to the case of N bodies is at the basis of the classical mechanics of systems.

25. The electrostatic action of N charged particles on one charged particle is a good example. It is a vector which is the sum of the N actions of each charged particle on the target one; although the single interaction is a nonlinear function of the mutual distance between two charged particles.

26. They are also the components of a vector in the direct sum that represents the vector in the given basis.

27. See, for instance, R.P. Feynman, R.B. Leighton, M. Sands, *The Feynman lectures on Physics*, *cit.*, Vol. I-1, pp.14-8 and seq.

28. On this point see, for instance, L.D. Landau, E.M. Lifshitz, *Course of Theoretical Physics*, Vol. I, *Mechanics*, 2nd Edition, London, 1969; and also W. Kölher, "Psychology and evolution", *Acta Psychologica*, 7, 1950. We recall that the basic relation of elementary Newtonian mechanics: $F=ma$, is invariant for reflection of the time coordinate: that is, by the change of the time coordinate t with $-t$. The reason is that acceleration is a second derivative with respect to time, and its sign does not change by changing t with $-t$. A very subtle discussion of the friction phenomena in relation with this point can be found in R.P. Feynman, R.B. Leighton, M. Sands, *The Feynman lectures on Physics*, *cit.*, Vol. I-1, 12-2.

conservative, and in this condition the total exchange of energy is the algebraic sum of the energy exchanges induced by each force.

The assumptions described above have a methodological character. An explicit dependence on time of elementary interactions excludes the repeatability of the experiments. When we require that elementary interactions be represented by conservative forces, we can predict completely the energy exchanges between the system and its environment, and between the parts of the system too. So, we can better revert the reasoning, and we can assert that these requirements follow on the decisions of having repeatable experiments, and of predicting completely the energy exchanges between the parts of the system, and between the system and its environment. This last decision, furthermore, is equivalent to the statement that we consider the system and its environment as being an isolated system, from which it immediately follows that the total energy is constant in the system so enlarged. Therefore, when we develop a theory, or when we apply it to a particular case, we have to enlarge our system to a part of its environment such that the system together with this environment part can be considered as being an isolated system. However, only experiments can prove whether the properties mentioned above, and their consequences hold for a particular physical process, because we have to prove whether we can pose a one-to-one relation between a vector and the values of the observables by which we manage the particular process. When they hold, in the theory we can substitute the occurrence of that physical process with the action of a conservative force.

In elementary classical mechanics we can geometrically depict the evolution of a system[29] as a path in a Euclidean space of 6 dimensions, the so-called phase space, and the path is defined as a mapping of the real interval [0,1][30] into the phase space. This representation is extended to more complex systems by assigning a suitable number of dimensions to the phase space. These dimensions are the number of observables we must use to characterize the state of the system. When we succeed in finding observables such that the state of the system at one time uniquely determines the state of the system at any later time, we know that the paths, which describe the possible processes, do not intersect[31]. This property can be reworded by saying that each path can be considered as being the effect of unique, specific set of physical facts: thus a bijection holds between this set of physical facts considered as being the cause, and the path considered as being the related effect.

When these conditions hold, a bijection holds between the causes and their related effects: that is, the causes unambiguously determine their effects, and from the effects we can unambiguously come back to the causes that determine their occurrence[32]. Figure 1 shows the effects of losing the property that the paths do not intersect. The left hand of Figure 1 shows immediately that, starting from the state A, we can have two possible paths: the path from A to B, and the path from A to C. The conditions that determine A may thus predict either B or C as possible future states of the system. On the right, the different conditions that predict the two states A and B can both predict state C as possible future states of the system. In this second case, the paths do not violate the requirement stated above when we move top-down. However, they might introduce contradictions in the theory when we assume that the elementary interactions are described by conservative forces, because the inverse processes do not satisfy the requirement that the related paths do not intersect in the phase space, and conservative forces lead to reversible processes.

The geometrical representation of a system dynamics by paths that do not intersect in phase space means that we succeeded in individuating a suitable number of independent observables, and in having confined the nonlinearities and the nonlocalities of the theory in the description of the paths. Further-

29. We recall that in this context a system is always thought of as being atomic, that is we do not consider it as being composed of parts.

30. This interval can be identified with an arbitrary interval of time by assuming a suitable scale factor, and we are interested only in finite intervals of time: $\pm\infty$ will be considered as mathematical limits.

31. A very clear and compact treatment of these topics can be found in J.L. Singe, *Classical Dynamics*, Encyclopedia of Physics, Vol. III/1, Springer-Verlag, New York, 1960, pp. 98 ff.

32. For the sake of simplicity, we cite the inertial motions of a mechanical system. For instance, the paths of inertial motions with the same momentum are parallel straight lines in the three-dimensional subspace of the phase space which identifies the spatial coordinates. To these lines we have to add the same point in the subspace of the phase space which identifies the momentum coordinates, and we obtain the possible future trajectories of such a mechanical system. Clearly the paths do not intersect.

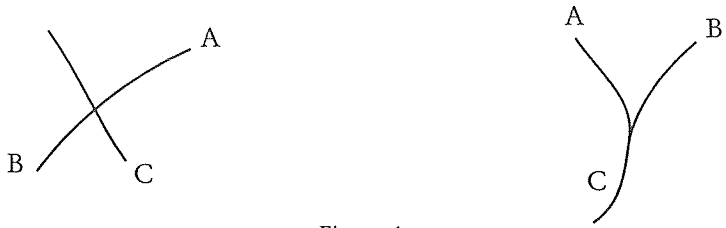

Figure 1

more, since we assumed that our systems are isolated, situations have no interest in which all the observables maintain the same value over a finite interval of time. In fact, an isolated system shall maintain that state for as long as it remains isolated. Therefore, we will assume that the dynamics of our systems shall always be represented by a line in the phase space, because, when it reduces itself to a point, we are not longer interested in it. Note that, although the dynamics of a system is described by paths which do not intersect in the phase space, this property does not necessary hold when we consider projections of the paths on subspaces of the phase space.

The conditions discussed above are severe, and we expect difficulties in satisfying them when we deal with biological systems. We do not find methodological obstacles to imagining a theory of the behavior of biological systems in which all the intermediate explanatory elements are physical processes that occur in the material and the architecture of a particular individual, nor do we find methodological obstacles in imagining that these physical processes are described according to the requirements discussed above. The practical difficulties are quite a different thing, because many of the systems that are studied by biology cannot maintain the architecture on which we are interested without exchanging matter and energy with their environment. This means that, without these exchanges, these systems lose the properties by which they are studied in biology, and very frequently they disassemble. For this reason it is frequently stated that biology studies open systems. Clearly this statement does not fit with our previous assumptions, and it would lead to a not optimal theory. So, in our methodological discussion we will not use the assumption that biological systems should be studied as open systems, although we are fully aware of the practical difficulties that are implicit in developing a theory in which we must include the dynamics of their environment.

As we have seen, a satisfactory physical theory of a system's behavior has to predict the energy exchanges between the system and its environment. This requirement again forces us to include in the theory a suitable part of the system's environment, so that we can consider the system and this part of its environment as being isolated with respect to the energy exchanges. Finally, all the energy exchanges must depend only on the initial and final state: that is, they must be independent from the path that connect the two states. This strategy has today severe limits in biology, because we usually do not know with sufficient detail the quantitative aspects of the energy exchanges in biological processes, and we always have poor knowledge of the parts of the system that are involved in these energy exchanges. Moreover, when we make *in vitro* experiments, these problems may be masked by conditions of the experiment that are often equivalent to postulating a practically unlimited source of energy. So, in biology the energy balance equations do not play the essential role that they have today in physics. In particular, we have great practical difficulties in dealing with a system that we consider as performing mental activity, and with such a part of its environment that we can consider this enlarged system as being isolated.

Scientific experiments lead to analogous problems, but a well-assessed strategy was devised to manage the difficulties. Since scientific praxis requires that experiments be repeatable, in each experiment we must study how a single variable depends on another single variable after having set the value of a certain number of other observables. The values of these last observables characterize the conditions in which the experiment is done, and must be carefully reproduced to repeat it correctly. When we can consider our system as one of the isolated systems discussed above, all the observables concern the system. When the system is only a part of such an isolated system, this part is designated as a system, and the remaining part of the isolated system is designated as an environment. In this case the observables that characterize the conditions in which the experiment is done may equally concern the system and its environment. The strategy consists in assuming that a surface separates the system from its environment. Then we substitute the value of the environment observables with the values of the observables on this surface, and these values must describe the interaction between the system and the environment at a given instant of time. Frequently these settings are designated as boundary conditions. However, if we refrain from extending the theory until we can predict the interactions between the system and its environment, this strategy shall allow only conditioned predictions of the system's behavior, where the conditions are the occurrence of a certain interaction with the environment. In this way we should really give up to predicting the behavior of the biological systems as they are classically defined, because, as we have seen, they are defined as systems that are open to exchanges of matter and energy with their environment. Therefore we must use the strategy described above only as a tool to simplify the management of the experiments, but we shall assume that a satisfactory theory must concern isolated systems as we discussed above.

Furthermore, a single experiment studies a particular aspect of the system's behavior: the relation between the dependent and the independent variables, having fixed certain conditions. Then it is up to the theory to integrate the results concerning different conditions. If our interest is only in steady states of the system, then we obtain a first level of integration by planning a series of experiments in which we impose different values on the independent variable, and in which the control variables that characterize the experiment have the same fixed values. In this way we obtain a relation between the dependent and the independent variables of the experiments, and this relation holds when the control variables have the fixed values assigned to them in the series of experiments. The theory usually requires several of these series of experiments to describe how the relation between the dependent and the independent variable depends on the control variables of the experiments. When the analysis of steady states does not give a satisfactory description of the system's behavior, we have a higher order of complexity because in each experiment we have conceptually to substitute the single value of the observables with a function of time[33]. This substitution raises methodological problems, because we cannot violate, even implicitly, the requirement that the experiments be repeatable. Furthermore, when a system is in a steady state, all the measurements of the observables refer to the same state of the system, even if a certain interval of time separates two measurements[34], and we can equally refer to the same state the value of an observable irrespective of the duration of the measurement. Both these very convenient properties do not hold when the system is not in a steady state. The measurement techniques thus become more difficult, and in the theory we have to decide how to relate the result of a measurement with the value of the observable that we introduced in the theory, or that we planned to measure[35].

Other practical difficulties arise from the number of elements involved: that is, from the number of dimensions of the phase space, and consequently from the bulk of information that we have to know. A reasonable estimate is that the human brain contains about 10^{11} neurons. This figure alone should force us to apply the approach and the techniques of statistical mechanics, and we must consider a considerably greater number of elements for obtaining a physical description with the characters outlined above. However, the most severe difficult arises because the interaction between our elements is typically nonlocal and nonlinear, as we will show in the next sections. In statistical mechanics, free-particle models are relatively simple although we have to deal with a number of particles which is in the range of Avogadro's number: that is in the order of 10^{24} particle per mole[36].

Despite the difficulties mentioned above, the characters that we proposed for the physical description have a very high conceptual and methodological importance. They characterize a reference theory which will be a good instrument to clarify the source of the various choices, and of the difficulties, in the physical and psychological description of our system's behavior. In the physical description, we

33. More generally, time here means an observable whose values have the mathematical properties of a totally ordered set.

34. This property is particularly useful when we have to determine the values of a function derivatives. Recall that the derivative of a function is a continuous linear operator at every point in which it exists. For real functions defined on a real space having finite dimensions, we thus need an array of values to characterize its derivative at a given point.

35. We have to decide whether we will use the measured value as the value of the observable at a certain instant of time, or as the average value over a certain interval of time. This point is discussed in great detail in W. Grandy Jr., *Foundations of Statistical Mechanics, cit,* particularly at the beginning of the Vol. 2, *Nonequilibrium Phenomena*.

36. See, for instance, W. Grandy Jr., *Foundations of Statistical Mechanics*, Vol. 1, *Equilibrium Theory, cit.*, Chap. 5.

have seen that it cannot be realized only due to the practical difficulty of obtaining and managing sufficiently detailed information about the interaction between the parts of a biological system, and between the biological system and its environment[37]. In the next sections we will see that in the psychological description we have conceptual reasons to set different requirements, mainly because we have very strong reasons to define mental things by using only part of the physical activity that we must introduce in the physical description of the system behavior. This choice will lead to a picture of the system dynamics in which properties are intentionally expunged as those of a dynamics that can be geometrically represented by paths that do not intersect in a phase space. Since our aim in this paper is to clarify the methodological differences between the two descriptions and their sources, hereafter we will systematically use as a reference for the physical description a theory with the characters stated above, and we will refer to it as the reference theory. We will refer also to a picture in which a system dynamics is described by paths that do not intersect in a phase space of suitable dimensions. I think that these differences can be identified also when we will use a more realistic physical description, and we will also consider quantum aspects of the dynamics of the biological molecules. Nevertheless, I did not succeed in tracing them with sufficient clarity, when I tried to give a physical description of the biological system's behavior by following the approach of the statistical mechanics.

In my opinion the conceptual scheme of the continuum mechanics[38] too could be a good formal tool to describe biological systems, particularly the more complex ones. If we use a point of view that thinks of the system as being composed by discrete elements, then the biological systems would have an extremely high number of elements, and it would thus become very difficult to manage, both conceptually and mathematically. Furthermore, in these systems there is a traffic of chemical molecules and ions of different sizes among the different parts of each cell, among the various cells, and among cells and their extra cellular matrix. The continuum with microstructure[39] probably would offer a better viewpoint, but some difficulties arise from our aim to introduce delay in the interaction. In continuum mechanics extension is atomic, rather than in terms of discrete elements. Thus, we do not define point values of the observables, but distributions, and we have to introduce fields to describe the interaction[40]. These facts should force us to develop the system dynamics with instruments that are slightly different from those discussed in this paper. So, we prefer not to deal with this possibility here. Furthermore, the probabilistic character of the predictions, which we obtain from certain theoretical approaches of physics, may mask the consequences of having defined mental things by using only part of the physical processes, and it can thus mask the different origin of the probabilistic character of the predictions. The similarity does not really go beyond the use of the same mathematical instruments to formalize a probabilistic approach.

We will conclude this section by mentioning that, after having defined the facts and the activities of interest in the theory, another essential topic is to describe the connection between the occurrence of the facts and the activities so defined. Two main strategies have been devised to accomplish this aim: we can describe the correlation between facts or activities, or we can describe the activity that causes each particular fact or activity.

In describing the correlation between the facts we may decide to use a deterministic or a probabilistic approach. The physical description of a system dynamics that we have outlined above is a good example of a deterministic correlation between the states of the system, and this correlation predicts which states will follow a given state of the system. We must be aware that in general we renounce to individuate which facts determine the existence of the correlation, when we decide to use only a correlation between facts. We usually indicate only the conditions under which the correlation holds. Therefore, even if we decide to use a deterministic correlation between the facts, we must be aware that we

37. When we are only interested in a limited volume of the phase space, and in a limited interval of time the picture described above can also have a practical relevance.

38. See C. Truesdell and R. Toupin, *The classical field theories*, Encyclopedia of Physics, Vol. III/1, Springer-Verlag, New York, 1960; C. Truesdell and W. Noll, *The non-linear field theories of mechanics*, Encyclopedia of Physics, Vol. III/3, Springer-Verlag, New York, 1965.

39. A good introduction is in G. Capriz, *Continua with microstructure*, Springer-Verlag, New York, 1984.

40. See for instance J. Glimm and A. Jaffe, *Quantum Physics. A functional integral point of view*, 2nd edition, Springer Verlag, 1987.

need further information to pass from a correlation between two facts to a cause-effect relation, because, when we assume a fact to be the cause of another fact, we require that the occurrence of this fact systematically produces the occurrence of the other fact. Indeed, the cause may be one of the facts that we correlated, but both the correlated facts may be effects of a third fact. Long and hard experimental work is often necessary to find suitable causes, because we usually require that a cause is specific: that is, we require a bijective function to hold of the thing that we consider as being cause into the thing that we consider as being the related effect. We must be fully aware of this point when we interpret a scientific result, and particularly when we forecast its practical applications.

Biology offers very interesting examples of such situations. When we know only correlation between a new behavior and some changes in the biological architecture, we are not sure that we will obtain the behavior by inducing, with the techniques of biochemistry or of molecular biology, the related changes in the biological architecture. We inherit from the history of biology an evolution scheme in which a new behavior grows together with the related changes in biological architecture. In these cases a correlation between the two orders of facts becomes a logical consequence, although suitable experiments are in any case needed to choose the things that we will consider as being respectively cause and effect. The availability of different means to induce changes in the material and the architecture of a biological system raises the problem of the weight that the system activity has in inducing a stable behavior. This problem is still a very open problem, despite the quantity of experimental data that have been collected, particularly on the development phase of biological systems. Since we have here a superimposition of different ways to modify a biological architecture, because now the activity is only one of these ways, it is not strange that the dynamics of the changes can become rather complex, and that we may find unexpected results[41].

Although we are fully aware of the difficulty of realizing a physical description of biological systems that fulfills the program outlined above, we will take this program as a reference point in our discussion, because it gives rise to a description which is conceptually very terse and clear. In the next sections we will continue our discussion by dealing above all with these topics:

- the description of memory phenomena both in the physical and in the psychological approach, and their related differences;
- the nonlinear and nonlocal character of the interaction among the parts of a biological system;
- the constancies of mental activity;
- the hypothesis that paradigms constrain the mental activity of the subjects, and the role that these constraints assume in the dynamics of mental activity.

Memory phenomena

In describing physical systems we usually speak of memory phenomena[42] when in the theory that explains and predicts the behavior of the system, the values of the variables that we have defined depend, at a certain instant of time, on the values that these and other variables assume both at the same instant of time, and on the past. Another, less general, way to characterize memory phenomena says

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41. Some interesting results are reported in V. Porciatti, T. Pizzorusso, and L. Maffei, "Vision in mice with neuronal redundancy due to inhibition of developmental cell death", to appear in *Vision Neuroscience*. They experimented with transgenic mice over-expressing *bcl-2, which, due to inhibition of naturally occurring cell death, have much larger brain and optic nerves as compared to wild type mice. By recording Local Visually Evoked Potentials (VEPs) from the primary visual cortex in response to patterned stimuli, they found that the representation of the visual meridian was displaced by about 15% in the bcl-2 mice, but visual acuity, contrast threshold, and response latency were normal, indicating that compensatory mechanisms can ensure normal basic properties of vision in spite of marked neuronal redundancy. Other behavioral experiments of this laboratory show that bcl-2 mice have normal visual acuity and normal behavioral performance in a T-maze apparatus (L. Gianfranceschi, A. Fiorentini, L. Maffei, and V. Porciatti, "Behavioural visual acuity of wild-type and bcl-2 transgenic mouse", Society for Neuroscience Abstracts, 1996,1060)*

42. A certain number of problems discussed in this section were discussed in R. Beltrame, "Memory and mental activity", *Methodologia*, 12/13 (1993), pp. 173-180.

that the response of the system to actions of the environment depends on these actions, and on the history of the system's activity. According to these definitions it becomes plainly evident that the presence of memory phenomena is generally the rule in biological systems.

The most immediate way of including memory phenomena in a physical theory is to imagine that the processes that occur in the system induce modifications in the material of which the system is made. These modifications usually satisfy a locality principle[43]: that is, the changes in each part of the material depend on what happened in the past time only to that part and to its immediate neighborhood. The consequences of these changes on system's behavior are often modeled through changes in the constitutive relations that describe the particular class of systems. Modifications of this type are thought of as being permanent too: that is, we assume their effects on the behavior of the system will be maintained until further modifications occur in the material. The technique offers several examples of objects in which this way of considering a physical system with memory is particularly evident: for instance the magnetic disks commonly employed in computers.

Functionals of the activity history can be used to describe these modifications mathematically[44]. Probably the best example of this technique is in elementary Newtonian mechanics. A functional of the history of the forces that acted on a mechanical body over a certain interval of time is a vector, and this vector describes how much the momentum varied in that interval of time. In this context the mechanical body is assumed as being unitary and as having a constant mass, so that the velocity is also a state variable. Since in biological systems we are equally interested in modeling phenomena of fading and forgetting, these functionals can take a rather complex form. Furthermore the changes in the material must be interpreted in a broad sense, because we can, for instance, invoke different concentrations of certain molecules in a part of the system, to explain why the same process causes different processes; or we can have that a protein A is a gene regulatory protein that activates its own transcription. If an action turns on the expression of the protein A, then all the cell's descendants will produce the protein A[45]. Therefore local changes in the biological material can be interpreted as architectural changes.

Actions of the environment are a conspicuous source of physical activity that induces changes in the architecture of a biological system, and it is a matter of experiment to describe the correlation between these actions and the physical processes that occur in certain parts of the biological system. For instance, it usual to designate as receptors the parts of the biological system in which particular processes are thought of as being caused by a specific environment action or by a narrow range of environment actions as the arrival of a photon whose energy is in a certain range, a specific molecule that binds and activates a transmembrane protein in a cell, and so on[46]. It is again a matter of experiment whether the actions of the environment are correlated or not. We can thus expect that a correlation between the environment actions will originate a correlation between the changes in the architecture of the biological system. Although we do not expect a simple link between the two types of activity, conceptually we have here an alternative both to an innatistic position, and to the untenable position that random events (that is, independent and equiprobable events) can lead to an organized architecture.

When we use a physical theory with the characters of the reference theory discussed in the previous section, we are dealing with an isolated system by decision[47], and so we have to think of the physical system as being composed of parts interacting with each other, otherwise we could not have any change. As we have seen, the elementary interactions between the parts of the system are represented

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43. See C. Truesdell, *A first course in Rational Continuum Mechanics*, Vol. I *General concepts*, New York,1977; and M. Silhavy, *The Mechanics and Thermodynamics of Continuous Media*, Springer, 1997.

44. In general these functionals may also depend on the past history of the time and space derivatives of the variables that we use to describe the system dynamics.

45. See B. Alberts, D. Bray, J. Lewis, M. Raff, K. Roberts and J.D. Watson, *Molecular biology of the Cell*, *cit.*, p. 444, and the related bibliography. Nevertheless, these last types of phenomena may also be formalized as phase transitions.

46. Note that we refer to the processes that are immediately started by the environment actions, because we will treat separately the actions induced by other parts of the biological system. Therefore, we do not mention things having the complexity of a rod in a human retina, but we think of rhodopsin in such a configuration that the arrival of a photon may start the chain of processes by which the rod fires.

47. Recall that we require the system to be isolated in order to predict the energy exchanges. By isolated system we mean the biological system plus a part of its environment such that their sum could be considered as being an isolated system.

in the reference theory as conservative forces, and they must not depend explicitly on time. Clearly we must define as many parts in the isolated system as are necessary to have well defined elementary interactions, and to obtain suitable explanations and predictions of the facts in which we are interested. In this framework, memory phenomena of the type described above become changes in the mutual positions of the parts of the system, because the spatial configuration of the system parts that support the elementary interactions defines the material and its characteristics. A locality principle is thus acceptable either because it has an experimental basis, or because we can deduce it by a definition of the material in a more analytic theory[48].

When we think of a physical system as being composed of parts interacting with each other, and we refer to a scheme in which the change in a physical quantity at a certain point in the system is considered as the cause of the changes of the same or of another physical quantity at a different point in the system, we have to decide whether a delay is significant or not between the occurrence of the cause and the occurrence of the related effect[49]. When this delay is significant, the values of a physical quantity at a certain point and time depend on the values that the same or other physical quantities assume at different points and at past instants of time. This delay is a characteristic of the interaction, and its properties follow from specific experiments. We can find it both in a theory with the characters of the reference theory discussed in the previous section, and in a theory that does not have these characters; indeed the effects too are quite similar. The delay in interactions thus offers a way to describe memory phenomena in physical systems, and it is noteworthy that in this condition the system shows phenomena of memory without us having to assume changes in the architecture of the system, and so also in the material from which it is made[50].

If the interaction between the parts of the system is active for a long time, then the past values of the variables that affect the actual value of the observables, may still depend on the values that certain variables assume in other points at earlier instants of time, and so on. However we must always describe the memory phenomena in a way that does not violate, even implicitly, the repeatability of the experiments. When we apply this requirement to the experiments, the relation between dependent and independent variables, and the fixed values assumed by the other observables that characterize the experiment must be invariant by translation of the time coordinate[51]. Clearly this requirement must also hold for the predictions that we deduce from the theory, and that we want to test by experiments. The requirement is satisfied when the description of the interaction has no explicit dependence on time; that is when the interaction can change only in dependence on the space position of the interacting elements[52], and a general theory must be grounded on these bases. The delay in interaction cannot be considered as being an explicit dependence of the interaction on time, but the state of the system now depends on the system's history, because we have a back propagation chain of dependencies on the past activity of the system. The repeatability of the experiments is easily assured when we succeed in defining state variables, because the knowledge of the value of these variables is equivalent to the knowledge of the system's history when we formulate predictions about the future behavior of the system. Unfor-

48. A concise discussion of this point can be found in C. Truesdell and W. Noll, *The non-linear field theories of mechanics, cit.*, Sect. 3.

49. When the effect in the interaction follows the cause with a certain delay, it is usual to speak of delayed action, or of delayed interaction, both when the cause and the effect occur at the same point, and when they occur at different points. When the delay is considered significant, and when cause and effect occur at different points, it is often satisfactory to express this delay as a linear function of the distance between the two points where the changes of the physical quantities occur; and, in this situation, the term 'propagation speed' designates the constant rate in the linear function. Nevertheless, the reasons for introducing this concept in a theory, with the related problems about a thing that would travel from one point to another, really concern the decision to write equations of balance for certain physical quantities, which must hold at every instant of time both for the system, and for its parts. A very good discussion on this point can be found in R.P. Feynman, R.B. Leighton, M. Sands, *The Feynman lectures on Physics*, Masson, Paris, 1991, Vol. II, pp. 27.1 ff.

50. We recall that the occurrence of memory phenomena of this type is very frequent in natural systems. Systems without memory are nevertheless of theoretical interest because of their simple mathematical treatment, and because the actual production of the artifact concerns systems with a behavior strictly stereotyped, repetitive: that is, a behavior that we want to be independent of the system's history.

51. More generally it must be invariant for translations of the completely ordered parameter that we use to describe a process. The interval [0,1] of the set R of real numbers is usually assumed as a prototype of the formalization of this parameter.

52. If we describe interaction by a field, this means that the field is stationary; that is, it does not depend explicitly on time.

tunately there is no general method to define state variables, and it is usually very difficult to define suitable state variables for a complex system. Alternatively we can assume that we know the history of an isolated system starting from a state that we can consider as being a steady state, but this condition is rather difficult to realize in biological systems, and it becomes quite impossible when we enlarge our system to a part of its environment so that we can consider the enlarged system as being isolated.

However, we can require a weaker condition. The repeatability constraint is fulfilled when the knowledge of the system's history over a limited interval of time is sufficient to formulate predictions about the future behavior of the system: that is, when the back propagation chain of dependencies on the past activity must stop in a reasonably short interval of time. Furthermore, when for a sufficient interval of time we have no interaction between two parts of the system, also the memory effects, which were induced by the interaction delay, cease on these parts. When we have interactions that concern only relatively limited parts of the system, and such that different parts are involved in performing a different behavior, then the interaction delay can exhaust its effects, because we can predict a decay of this type of memory when activities alternate, which involve interactions among disjoint parts of the system, or, at least, which have as target disjoint parts of the system. We thus expect that the effects of this type of memory decay, when we alternate very different activities, and we know that such an alternation usually reduces fatigue. We may think that a good contribution to the decay of this type of memory, both in man and other mammals, be given by alternating two periods in which we have a very different activity: a diurnal conscious activity, and the nocturnal sleep.

In biological organisms we have cells that die and are replaced by new ones at rather regular intervals of time, and many constituents of the cell are regularly replaced. At the level of a single cell we have, for instance, continuous phenomena of endocytosis and exocytosis, and, more generally, soluble, or secretory proteins, and other substances are thrown in the intracellular space, and are imported from it. Newly synthesized plasma membrane lipids and proteins replace the old ones. Indeed many of these processes can be also receptor-mediated, and so they can be modulated by actions of the cell's environment[53]. We may think that these substitutions of old biological material with new material contribute to canceling the link with the past activity that is induced by the interaction delay, and we can thus explain why the possibility does not fail to repeat the experiments, although the interaction delay introduces a dependence on a back chain of past facts.

When the system we are concerned with occupies a region of space such that we can neglect the delay of the interaction, we can simplify the study of the particular case by substituting the knowledge of the external actions with the knowledge of the values that significant physical quantities assume on a closed surface that envelops the system, and this way of studying a physical system is frequent in laboratory experiments. However, we must have a satisfactory theory which can predict the values of these physical quantities on the closed surface that envelops the system[54], and the energy flow across this surface. Otherwise this approach would become a source of problems when we try to use the result for developing a theory, or to transfer the results from *in vitro* experiments to *in vivo* systems.

The two ways of describing memory phenomena (one employing permanent changes in the material of which the system is made, the other using the delay of the interaction among the various parts of the system) provide different and complementary facilities to treat memory phenomena in the physical description. In psychological descriptions different ways are in use, besides the relation with the memory phenomena as they are treated in a physical description. Although we can use the delay between the occurrence of mental facts that we consider to be correlated, we have situations in which the introduction of a specific mental activity seems to be a very reasonable solution. In particular, a reasonable hypothesis seems to introduce a mental categorization for describing conscious memory phenomena.

Mental facts can be described by regarding them as activities and by giving their constitutive operations. In this framework it was proposed that, when we speak of a mental fact as being a conscious memory, the mental fact is considered as a repetition of another mental fact, and the latter is considered

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53. A good synthesis of the endocytosis and exocytosis phenomena at the level of single cell can be found in B. Alberts, D. Bray, J. Lewis, M. Raff, K. Roberts and J.D. Watson, *Molecular biology of the Cell*, *cit.*, Chap. 13.

54. Another way of describing this difficulty is that we must know which physical processes produce the observed values of the physical quantities on the closed surface that envelops the laboratory system.

as having occurred in the past[55]. Following this hypothesis a mental fact becomes a conscious memory as a result of a mental categorization, which follows the scheme described above. Two sets of conditions thus constrain the occurrence of a conscious memory. A first set concerns the possibility of executing the constitutive activity of the mental fact that should be the content of the conscious memory. The second set concerns the categorization of a mental fact as being a repetition of a mental fact that occurred in the past to the subject of the conscious memory. We thus expect a selective loss of the conscious memory of those facts that a subject cannot produce as mental facts for any reason, although they occurred many times in his past. Achromatopsias are known, which follow from brain lesions, in which an adult man loses the ability both to perceive and to remember colors, even if he had perceived and remembered colors several times before incurring the disease.

We do not succeed in defining a mental categorization by means of an injective function into suitable physical processes that occur in the system we think of as performing the mental categorization. In particular we do not succeed in finding suitable elements to characterize the conditions that lead to the proposed categorization in a context where conscious memories may arise. We have in fact to explain why in a certain moment a person considers a certain mental fact to be the repetition of a past fact, and we also have to explain why the subjects report facts that are sometimes the same as the ones that occurred, and sometimes they are different[56]. This is a strong limit, because we cannot explain and predict whether a conscious memory will occur, its contents, and the moment in which it will occur to a particular subject, and the integration with the physical description of the system dynamics becomes unattainable. Our discussion can only be of the type: if a certain conscious memory occurs in a given context, then we can predict the following consequences.

From the occurrence of the mental categorization described above, we can expect that thinking of one thing as being a repetition of another, might also imply thinking of the two things as being equal. Furthermore, in the comparison that is part of the constitutive operations of the equality, the proposed categorization scheme implies that we use as a paradigm what is thought to have occurred in the past. We become aware of this fact when we find a disagreement with this paradigm, for instance by means of factual or document checking, testimonies, etc. In these conditions we usually decide to explain the failure of the equality that we expected as a consequence of the applied mental categories, by inserting suitable causes. Since expectations commonly arise from mental categorization, when no check occurs, the subsequent behavior continues as if the expected consequences held[57]. This behavior, which is quite general, as we shall see below, assumes particular relevance in our case. What we consider as being a memory (and is thus considered as a repetition of something that occurred in the past), is considered to be a repetition of something that occurred in the past concerning the subsequent behavior too. The stimulus is then weakened to check whether the conditions hold to apply the categorization scheme proposed for the conscious memories, and this effect will become progressively stronger when such a situation is repeated. Motivations, of which the person might not be completely aware, can strengthen the tendency to avoid checks. Furthermore, a subsequent memory can base itself on a previous one, rather than on the original situation: that is, in the categorization the person assumes the actual mental activity to be a repetition of the one which occurred in a previous memory, thus applying a type of transitive property. The consequences are well known, we can have facts that the subjects consider as being good memories, which may either result as not having occurred, or, when a check is performed, reveal significant differences from those a person considers as memories. Since the persons consider these facts as really pertaining to their past life, we may have relevant consequences on their behavior, which are particularly evident in mental diseases.

We can apply with no difficulty the way of considering conscious memory, which we proposed here, to a celebrated case in Freud's development of psychoanalysis[58]. Freud reports that many of his

55. This characterization was proposed in S. Ceccato, *La fabbrica del bello*, Rizzoli, Milano, 1987, pp. 234-36 (in Italian). It is also interesting to see the Aristotle's discussion on this point in his *De Memoria*, *Parva Naturalia*, 450a.25 ff.

56. Clearly equality and differences result here from a comparison between what a subject reports as a memory, and the contents of a physical record of the fact which the subject is talking about.

57. We avoid talking about consequences that are assumed to be true or verified, because a check is implied, which was excluded by hypothesis.

patients remembered, under analysis, seduction situations (that is, passive sexual experiences) that they claimed to have suffered during their childhood; but these memories turned out to be untrue when a later check was made on the patient's history. We can remark that a gesture of affection frequently assumes sexual connotation after sexual differentiation is completed in adolescence, particularly when it involves the tactile sensory system. So it becomes impossible that certain demonstrations of affection, and specifically those involving the tactile sensory system, give rise to the same sensations that they provoked during childhood. Let a person starts from the memory of affection gestures that involve the tactile sensory system, and in that moment let him be not fully aware of the difference discussed above. He will give a sexual connotation to those gestures even if the lack of awareness is not systematic. Furthermore, because he now feels these gestures with sexual connotation, he also considers them thus connoted as a good memory of what he felt during his childhood. Clearly the conclusion is acceptable from a psychological viewpoint, as Freud asserts, but it is not plainly acceptable as a proof of the occurrence of an intentional seduction. We need a suitable check. However, the consciousness of these differences follows from a thought activity. So, it requires the person to agree with a paradigm that is transmitted by culture. The content of this paradigm is precisely that the differences discussed above are introduced in our feelings by the biological process of sexual differentiation during the adolescence, and that a sexual attraction or repulsion concerns only persons that have reached this level of sexual differentiation[59].

The characterization of the conscious memories as involving a mental categorization is also compatible with a possibility that is particularly attractive for long term memory, particularly the memory that spans over months or years. Let we decide to describe the cognitive facts as being the result of constitutive activities, to which certain physiological activities will correspond. When we take this point of view a cognitive fact and a scheme of movement will have the same kind of description and of physiological interpretation, because both are activities that the subject performs. Furthermore they have the training as the same scheme of learning, because the subject has to become able to execute certain activities. In these conditions the conscious memory can arise in two steps. The first step involves the procedural memory by which we are able to perform a certain mental activity; the second step is the categorization outlined above, that is the activity by which we consider the actual cognitive fact as being the repetition of a cognitive fact occurred in the past. For instance the persons are able to represent mentally the face of their parents, and this ability can be ascribed to procedural memory; then a conscious memory arises when they categorize the mental representation of their father face as being the repetition of a cognitive fact that occurred in the past. In particular we expect that, when we acquired the ability to perform the constitutive activity of a cognitive fact, yet fading and forgetting will follow the same rules and the same dependence on aging of other facts that we usually ascribe to the procedural memory: for instance the schemes of movement. The loss of memory by effect of aging, in fact, does not concern the well-assessed things, but the memory of what happened in the past minutes, or hours, with the related consequences.

Other memory functions that were introduced in the descriptions of the psychology may involve mental categorization. In physical descriptions, on the other hand, we can only use the two schemes discussed at the beginning of this section: changes in the material, and delay in interaction.

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58. We will quote Freud's first communication in his letter to Fliess of September 21, 1897: «Then the surprise that in all cases, the father, not excluding my own, had to be accused of being perverse - the realization of the unexpected frequency of hysteria, with precisely the same conditions prevailing in each, whereas surely such widespread perversions against children are not very probable. The incidence of perversion would have to be immeasurably more frequent than the resulting hysteria because the illness, after all, occurs only where there is a contributory factor that weakens the defense. Then, third, the certain insight that there are no indications of reality in the unconscious, so that one cannot distinguish between truth and fiction that has been cathected with affect.», and later he notes: «It seems once again arguable that only later experiences give the impetus to fantasies, which hark back to childhood, and with this factor of a hereditary disposition regains a sphere of influence from which I had made it my task to dislodge it - in the interest of illuminating neurosis.» S. Freud, *The complete letters of Sigmund Freud to W. Fliess 1887-1904*, transl. J.M. Masson, Harward University Press, Cambridge, 1985, pp. 264-5.

59. This picture again agrees with Freud's analysis of pathological behavior. The critical point is the equilibrium between thought and sensations. Furthermore, when the cultural paradigm is not accepted, the subjects can suffer the consequences of feeling the sensations that they attribute to the partners of the imagined sexual act. Depending on the distribution of pleasure and repulsion between the partners, we can explain the wide range of reactions that Freud clearly described and studied.

The nonlocal and nonlinear character of the dynamics

In this section we will briefly discuss two global aspects of the dynamics of the systems that we consider as being able to perform mental activity: the nonlinear aspects of this dynamics, and its nonlocal character. We start with the nonlocal character, which is more immediate.

In a theory of systems such as crystalline solids, we may think that the interaction among the parts of the system only involves the neighboring elements of each element: that is, the interaction intensity slows down very quickly with the distance between the elements. A theory thus gives good results in which we introduce an interaction of each element with only the few elements immediately surrounding it, and in which we think that this situation holds for all the elements of the system. Clearly we have an exception for the elements on the system boundary with the environment. The interactions of these boundary elements determine a large part of the system's interaction with its environment; the other part being described as a further interaction of each element with an external field, that is an interaction with a field that we think of as being caused by other physical systems.

In biological systems, on the other hand, we find two phenomenological data that prevent us from assuming a short range interaction as a general prototype of the interactions among the parts of the system. A piece of cat does not behave like a cat; instead a reasonably small amount of sodium chloride behaves like sodium chloride. Therefore the description of the interaction among the parts must have considerable differences in biological and in physical systems, and different theoretical models are required. If macroscopic parts lose the behavior in which we are interested when we isolated them from the surrounding ones, then we must add to the theory significant interactions among distant parts of the system. We will also have to add actions of the environment onto the system; because we again observe that, when an environment action ceases to act, this fact causes the loss of the behavior we are interested in. This situation usually occurs in every cell: thus, it is almost the rule in biological systems.

Indeed, in biological systems we frequently observe the degeneration of the parts that become excluded, for any reason, from interacting with other parts of the system, or with the system's environment. In some conditions this lack of interaction induces a change of function; for instance when we observe a modification of the extension of the cerebral cortex areas interested in visual, auditory, and tactile activities, as a consequence of lesions or diseases that strongly reduced the visual or auditory function. In other conditions we can see, particularly in animals, a voluntary behavior in order to deprive oneself of a body part that has lost its functionality, for instance as a consequence of a lesion. Finally, if the long range interaction ceases for a certain interval of time, then the system rather quickly loses its interconnections and its stability, so that, at room temperature, it starts to decompose itself[60].

Like other physical systems, biological systems maintain their stability over a certain range of conditions. The changes in these conditions are often started by actions of the environment, and they occur when the system is in a certain state. So, they may favor the stability of the system, or they may tend to disassemble it. Even if they do not desegregate the system, they modify the system's architecture, and thus its functionality, as we discussed in the previous section. A biological system must thus be conceived as a dynamic system whose changes follow certain general rules. The changes are provoked, somewhat directly, by the environment actions that occur during the system's life. This means that also the interactions that ensure the system's stability may change through the life of a biological system.

Since in biological systems we have long range interactions, and since the system's stability requires an intense activity, we can expect that at least two ways of storing energy will be significant. The most frequently mentioned way is the presence of molecules that participate in chemical reactions which a release of energy is associated with. ATP (adenosine 5'-triphosphate) is one of these molecules. The second way is the energy exchange between parts of the system such that the loss of energy is very low during the exchange. The mathematical prototype of this energy storage is the harmonic oscillator, but every periodic process may in principle be a good candidate to store energy in this way. Significantly,

60. It is common knowledge that we have to maintain the biological material at a reasonable low temperature to preserve its architecture, and to avoid its decomposition. A computer card, instead, has a reasonable stability at room temperature both when it is functioning in a computer, and when it does not function, for instance, because it is not powered.

biological systems show many periodical processes. We thus have two ways to think of the process of storing energy in our systems, and their dynamics is different.

Despite the strong necessity to take into account interactions among remote parts of biological systems, some aspects can be studied separately, and a good example of this strategy is the theory of various types of the so-called receptors. We think of receptors as elements that respond to environment actions only in a narrow band, and with a high gain. The main problem of receptors' theory is the correlation of the receptors' activity with the physical actions to which they can respond, and the very high specificity of the interaction allows us to study separately many kinds of sensory receptor. When we are dealing with a physical description in which we have defined an isolated system, the activity of the receptors is described by a cause-effect relation between some physical processes that occur in certain parts of the isolated system.

When we have environment actions that depend on previous actions of the system we are forced to consider in the theory a suitable part of the environment. Voluntary actions that modify the subject's environment offer a good example of this necessity. Actions onto the environment, which imply the activity of muscles, determine the actions of the environment on the sensory receptors, which follow from the previous surrounding modifications, and in the theory we must connect these activities. This situation occurs just for a simple, voluntary displacement of an object, but it also occurs whenever we introduce boundary conditions. With this extension we are practically dealing with an isolated system, like in the physical theory that we proposed as a reference theory in our discussion.

We will now discuss two main topics about nonlinear aspects of the dynamics: the nonlinearities that arise from using a constructivistic approach in psychological descriptions, and how, in a physical description of our system's behavior, a nonlinear dynamics may also arise from elementary interactions that have the characters that we require for the reference theory.

In a psychological approach we frequently use the strategy of defining cognitive facts by decomposing them into other, more simple ones, and their mutual relations[61]. In this way we obtain a more compact description of cognitive facts, because the description is based on a low number of facts and relations, which are atomic in the scheme of analysis. Recall that they are atomic either because we do not succeed in further decomposing them by using the same criteria, or because we decide to stop the decomposition at a certain level of granularity.

When we wish to build a theory starting from a decomposition of the type described above, we thus have a certain number of elementary situations, and one or more composition laws of the elementary situations. The form of the composition laws will be independent both of the number of components and their order; otherwise we would have to devise a different theory for every different compound and so we do not have the general theory that we usually require. Clearly the result of the composition depends on the components and, possibly, on their order too. However only a linear law of composition ensures that the result always has the same properties as the components, but we pay this very nice and general property with the constraint of combining only elementary situations of the same type[62]. Thus we cannot use a linear law of composition when we want to compose elementary situations of a different type, or when the result has different properties than the components. On the other hand, when we use a nonlinear law of composition, we can combine elementary situations of different types, but we must check by means of experiments that the properties of the compound subsist, which are predicted by the current theory, because now they do not follow from logical reasons. Furthermore, we have to investigate possible new properties of the compound, and we must devise a theory that will explain the new properties of the compound starting from the properties of the components and of their mutual relations.

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[61] This strategy was extensively used by S. Ceccato in "A Model of the Mind", *cit.*; and particularly by G. Vaccarino in his papers on mental categories. See, among others, G. Vaccarino, "Elementary categories I", *Methodologia*, 3 (1988), pp.5-72; G. Vaccarino, "Elementary categories II", *Methodologia*, 4 (1988), pp. 7-61; G. Vaccarino, *Prolegomeni - Vol. I*, Roma, 1997; (all in Italian).

[62] The electrostatic action of N charged particles on one charged particle is a good example. Here the resulting action depends on N, but the type of composition law does not. We have the same theory for every value of N, and the resulting interaction has the same properties as the components, because the composition law is linear.

The classical theory of electromagnetic field gives a clear example of this state of facts. We take an electric charge, for instance a little sphere with a positive charge, and we move this sphere at a certain velocity. We may try to predict the resulting effects as a combination of two situations whose theory is well known, the electrostatics and the elementary mechanics. However, new effects arise, because we obtain a magnetic field too. These further effects are properties that we cannot logically deduce by electrostatics and elementary mechanics, and their knowledge must be obtained by experiments on the situation that results from moving a mechanical body that carries an electrical charge. These experiments are necessary to describe the dependence of these effects on other observables, and then to enlarge the theory. Because the experimental situations have changed, we still need further experiments to check whether the relations among the observables continue to hold, which were predicted by classical mechanics and electrostatics, that is, by the theories of the two situations from which we started. Here, again, only experiments can decide the changes, and we know that in general the laws of classical mechanics and of electrostatics do not hold, but we have to amend them so that they give results that agree with the experiments in the full range of conditions[63].

It is outside the scope of this paper to discuss how in physics a theory of the electromagnetic phenomena was obtained, which satisfies the methodological requirements stated in the previous sections[64], but this example shows a situation that occurs rather frequently. When we combine elementary situations of different types we are using a nonlinear law of composition, and we cannot predict the properties of the compound by deducing them logically from the properties of the components. In physics, as we mentioned above, we must use experiments to check whether the properties of the compound subsist, which are predicted by the current theory, and to investigate possible new properties of the compound. In mathematics we usually define new objects, and we must deduce what is implicit in these new definitions. We have an example of this procedure when we think that a geometrical entity with the characters of a surface can be obtained by composing entities with the properties of a line. If the lines are straight lines, the surface is a plane, and on the plane we can define a new class of geometrical objects, angles, whose properties we have to deduce from a new definition, because they could not be defined on a line.

A nonlinear composition law also implies that causes cannot be considered as being independent. Models thus become useless whose global properties and dynamics follow from statistics in which we assumed the elementary interaction to be independent, or equally probable. When we take an approach that uses the correlation between the observed events to explain and predict the system's behavior, we expect acceptable results only from models in which a strong correlation was introduced between the events, because we expect that a scheme of random, independent events does not give satisfactory predictions. However we shall also expect the related mathematical difficulties. Furthermore, in the experiments we cannot work with Boolean variables: for instance the presence or absence of a chemical substance. In a linear dynamics the dependence on one parameter does not alter the dependence on other parameters, and we can correctly study the dependence on one parameter by masking the dependence on the others. In a nonlinear dynamics this strategy may give worse results, because we can have a dependence on the product of two or more parameters, and a zero value of one masks the dependence on the others. It is a general fact that in each experiment the relation between dependent and independent variables depends on the values of the parameters that characterize the experiment. In a linear dynamics the dependence law is known by definition. A nonlinear dynamics, on the other hand, imposes a more cumbersome work because we must devise a suitable dependence law by performing an appropriate number of experiments with different combinations of the values of the parameters that

63. We know that, when the velocity of the charged sphere is relatively low, the surfaces having the same electrostatic potential can again be considered as spheres with the center on the moving charge; that is the same theory holds that we find when the charge is at rest. When the velocity is near the velocity of light in a very rarefied gas (the so-called void), these surfaces must be considered ellipsoids, Lorentz's transformations hold, and the mechanical momentum becomes a nonlinear function of the velocity. More details can be found, for instance, in R.P. Feynman, R.B. Leighton, M. Sands, *The Feynman lectures on Physics, cit.*,

64. Recall that the magnetic field generated by a moving electrical charge depends on the velocity of the moving electrical charge; so, in this formalization we have a first time derivative, and it is not invariant under time reflection. We know, however, that we can introduce a vector and a scalar potential, thus transforming the original formalization into an equivalent one which has the required properties.

characterize the single experiment. These situations are often described as situations where we have synergies, and the number of experiments required becomes considerably greater than in the case of a linear dependence.

When we consider a mental fact as being composed of other, more simple, mental facts, this composition typically has a nonlinear character, because the increasing complexity of a mental fact is usually referred to the addition of elements having qualitative differences, and a linear composition law requires that we only add different quantities of the same thing. Therefore in studying the dynamics of mental facts, we must expect that each new fact will require a particular study to determine its properties, because these properties cannot normally be deduced from the properties of the facts that we used to define it by composition. This difficulty is probably the main difficulty of the classical logic; but it also strongly reduces the practical interest in a constructive viewpoint when we define mental facts or activities. From a nonlinear composition law we also expect the existence of a strong correlation between the occurrence of mental facts and activities, and so we are led again to the necessity of a nonlinear dynamics in both a psychological and a physical description of the system's behavior.

In psychology a very classical example of nonlinear composition is given by Ehrenfels' qualities, which marked the beginning of Gestalt psychology. However, we can find more subtle examples in mental categorization, where it is not plain whether the result is given by the sum of the activities which correspond to the mental category and the thing categorized taken in isolation. We may have an activity which shares some features with those of the constitutive activity both of the mental category and of the thing we are categorizing, when isolated. Furthermore, the categorized thing usually acquires further properties which depend on the properties of the components when isolated, but which do not belong to the properties of the isolated components.

A constructivistic approach must be used with caution also to define mental facts and activities. We always obtain the physical process which corresponds to a cognitive fact, by composing the physical processes that we used to define the components of the cognitive fact and their mutual relations. However, the mutual relations can raise difficulties, because sometimes these relations are constitutive of the mental thing that we are defining, and sometimes they are constitutive of the mental activity with which we describe the definition of the mental thing in a constructivistic approach. For instance, when in our definitions we choose an injective function into physical processes, if we think of a sequence of processes, then we must indicate the place of each process in the sequence, and if we think of a complex process, then we have to indicate how the component processes relate each other. In conclusion, we can use a constructivistic approach in defining mental facts or activities, but with the care discussed above; and we must be aware that this approach does not significantly simplify our study of the properties and of the dynamics of the things so defined.

When we look at a physical description we can recall other situations that we know give rise to nonlinearities. Although we describe the interactions between physical things by means of conservative forces, these forces might not depend linearly on the independent variables of the particular process that we use to produce the interaction. For instance, we put two electrically charged bodies at a certain mutual distance to produce electrostatic forces. Experiments show that electrostatic force is conservative, but it depends on the product of the two charges, and on the inverse square of the mutual distance between the two charged bodies. In these conditions the behavior of the charged bodies is described by nonlinear equations, and this conclusion continues to hold when we have a system composed by many parts, although we can linearly combine the conservative forces that describe the interactions between these parts[65]. Other sources of nonlinearities may arise when in the physical theory we do not succeed in describing interactions by means of conservative forces. In this case the energy exchanges also depend on the particular process that the system is performing, and a principle of superposition does not hold.

When we think of the possible sources of nonlinearities that we discussed above, we find that the physical description of the biological systems which we are concerned with shows many situations that

65. Recall that when we are dealing with physical systems that cannot be considered as being isolated, the principle of superposition requires linear boundary condition to hold as well.

lead to a nonlinear dynamics. For instance, the physical description of the memory phenomena, which are highly significant in our systems, leads to a nonlinear dynamics, as we have seen in the previous section. The kinetics of two parallel chemical reactions, which involve a common molecule, leads to non linear differential equations, even if we do not consider diffusion phenomena. Finally, the generation of an action potential at the axon hillock of a neuron follows a nonlinear dynamics. We thus find nonlinearities at a very elementary level of the physical description.

Constancy phenomena and mental categorization

When we take the viewpoint of psychology, we find constancies in behavior although the same set of environment actions, to which that behavior was connected, will be repeated identically with a very low probability[66]. The physical actions of the environment which we consider as being atomic in our theory, can occur identically several times, and this fact has a methodological character[67]. However, we know from the theory that they do not induce the external behavior of interest for the psychology when they occur alone. To induce such a behavior a set of these atomic environment actions is required, and the same set will occur identically after a reasonable interval of time with a very low probability. Among the circumstances, and the environment characteristics that have a low probability of being repeated identically, we can cite the spectrum and the intensity of enlightenment, the mixing of objects in a visual field, and their distances, the spectrum of sound waves, etc. Classical constancy phenomena in the psychology of perception offer a good example of these situations. For instance, the subjects usually report that they see their hands as having the same size in a certain range of distances, though the visual angle is very different, and the extension of the stimulated region in the retina too. We see the object of the same color through a great range of light colors and intensities. Many conditions influence the occurrence, and particularly the strength of the constancy phenomena in visual perception. Significantly, size constancy is more evident for our hands, whose distances are in the range of reaching and grasping, and it fails when we look at a photo of the two hands placed at different distances. The constancy of colors is more evident when objects are involved whose color is well-known to us. Furthermore, constancies are particularly evident in the adult life of complex biological systems. We will discuss these topics in the next section, when we discuss the dynamics of the constraints on our mental activity.

Since our aim is to integrate a physical description of our systems dynamics with a description that follows the viewpoint of psychology, we will discuss how we have to interpret the description of constancy phenomenon that we have given above so that it becomes compatible with the reference physical theory discussed in the previous sections. We recall that the physical theory which we decided to assume as the reference theory requires that the state of the system individuates the future states of the system. As we have seen, this requirement has a methodological character, and we can reword it as the requirement to relate the occurrence of the causes with the occurrence of their effect by a bijective function: that is, from the occurrence of the causes we want to infer the occurrence of the related effect, and from the occurrence of the effect we want to infer the previous occurrence of the related causes. In a geometrical representation where the system dynamics is represented by paths in a suitable phase space, our requirement is equivalent to having paths that do not intersect in the phase space, or rather, we must define a phase space with such a number of dimensions that the paths do not intersect. We recall that we also decided that the system would be an isolated system: that is, our theory must concern the union of the biological system and of a part of its environment such that this union can be considered as approximating adequately the properties of an isolated system[68]. Indeed, we recall that still this last requirement has a methodological character: it is equivalent to requiring that we can fully predict the energy exchanges which interest our system dynamics. Finally, we recall that we decided to define men-

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66. In this section we will speak of environment actions because it is a common usage in psychology. When we consider our system as being an isolated system these actions simply become actions of certain parts of the enlarged system on other parts.

67. In fact we must choose atomic actions that satisfy the repeatability requirement, and, because we assume them to be atomic, they must have the possibility to reoccur identically.

68. We recall that by definition an isolated system has no exchange of energy with its environment. So, it also has no exchange of heat, charge, or mass with its environment.

tal things through an injective function into a subset of the physical processes that are necessary to give a physical description of the dynamics of our system: that is, by using only part of these physical processes. In a geometrical representation where the system dynamics is described by paths that do not intersect in the phase space, mental things become defined by projections of path segments into suitable subspaces of the phase space. As we will see immediately, this last point offers a common framework to interpret the various situations that we will discuss in this section.

Let us consider in a physical description the two sets of processes that are involved in the previous description of constancy phenomena: that is, the set of physical processes that are the counterpart of environment actions in the psychological description, and the set of processes that are used to define the constancy content in the psychological description. Geometrically we cannot think of these two sets of physical processes as being represented by segments of the path that describes the system evolution in the phase space, because this interpretation would violate our decision to have a bijective function of the causes into their effects. We must instead think of them as being represented by projections of segments of this path into suitable subspaces of the phase space, and these subspaces can be different for the two sets of processes. This statement is simply a rewording of our previous characterization of constancy phenomena. However, since the physical process that we used to define the content of the constancy is represented geometrically by a projection of a path segment onto a subspace of the phase space, it can be a projection of different segments of the same path, and of segments of many different paths. Therefore, different processes can precede it, but this representation highlights other important consequences. The process that we consider as being the counterpart of stimulus in constancy is still represented geometrically by a projection of a path segment onto a subspace of the phase space. Many paths can share this projection, and so it cannot be assumed to determine the following activity of the system[69]. As a consequence of these deductions we cannot try to obtain a unique cause for each constancy, and thus a unique explanation of its occurrence either, because this program is contradictory.

We have phenomena that are analogous to constancy when we recognize the same object in different contexts, because the occurrence of the same pattern of environment actions would be predicted in these cases with a very low probability. We have effects on the subsequent behavior, which are analogous to the effects of the perception constancies, also when we categorize a thing in certain ways: for instance when we categorize a thing as being the same after a certain delay in time, although some characters may be different. This situation is particularly evident when the time interval is large, and it is quite common, because it occurs when we use many verbs of our languages: typically the verbs with which we describe that a thing changes some of its characters.

If we assume the constitutive activity of the mental category to be the same although the related mental categorization may concern different things, then mental categorization becomes another situation analogous to constancy. Since we do not have a definition of the mental categorization with the characters stated at the beginning of this paper, our assumption is justified only because we must not give further definitions to the general notions that we decided to map into mental categories, such as cause, effect, singular, plural, some, other, and so forth. When we gain more insight into mental categorization, this assumption might maintain the characters of a choice: like the choice of assuming the charge to be independent of the velocity of the moving charged body in the experiments. However, a situation like the situation of chemistry might be more probable. In a chemical molecule the bounded atoms only have a certain number of the characters of isolated atoms on which classical quantum mechanics was built. In the theory of the chemical bond we can continue to use the wave functions that were obtained from the theory of isolated atoms, but we introduce a more complex tool, a linear combination of a certain number of them. In this way a further term is introduced into the computation of the bond energy which allows us to obtain more realistic results[70]. In mental categorization we expect

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69. We can restate the previous statements without assuming that the dynamics of the system are represented by paths that do not intersect in the phase space. In defining the environment actions and the contents of the constancy, we can say that we use less parameters than those that are necessary to characterize the physical activity in such a way that a bijective function holds between the processes considered as being causes and the processes considered as being the related effects. However, the phase space picture has an immediate evidence that can be useful in the discussion.

70. A very clear discussion of this point can be found in L. Pauling, *The nature of the chemical bond*, Third Edition, Cornell Univ. Press, New York, 1960, particularly on pp. 215-220, where the nature of the theory of resonance is discussed.

Figure 2

an analogous situation. In any case recall that mental categorization results from a nonlinear composition, because the components are different. The properties of the result must thus be studied in each case, and we must expect no general deduction to hold from the properties of the components.

We also observe phenomena that in a certain way are the inverse of constancy, because we observe different behaviors to be related to environment actions that we usually assume to remain equal. Classical figure-ground alternations are good, controlled examples of these situations: for instance, the well-known Rubin figure-ground alternation where we sometimes see a pair of faces, and sometimes a black vase (Figure 2 left), or where we alternatively lose as face the left or the right part of the figure (Figure 2 right)[71]. Besides these experimental figures, we have many situations in which different behavior can be related to environment actions that we usually assume to remain equal. For instance, the pattern in Figure 3 may be designated as a line, or as an angle. However, we can also accept that someone talks of a black pigment on the white paper of a page. In the framework of the Italian Operative School[72] this example was frequently used as a didactic tool to make a person aware of the role of mental activity, and to break the idea of a one-to-one link between a physical description of the situation that is used as stimulus, and the occurrence of a certain mental fact, or of a certain linguistic behavior[73]. Perspective is another situation of this type, because a two-dimensional pattern leads us to perceive the room and the objects represented as being three-dimensional. This habit is today very strong, and we usually cannot escape it, because camera images, particularly the images that we see on television, are very frequently linear perspectives[74]. Nevertheless, we can see a perspective pattern as being two-dimensional, for instance when we are drawing it as an application of geometry, and we have again the possibility to think of the pattern as pigment on its support: paper, canvas, table, or wall.

The remark that we made about the physical description of constancies also applies to the situation presented above. Let the dynamics of the system can be represented by paths that do not intersect in the phase space of a system which is the biological system and the part of its environment whose union

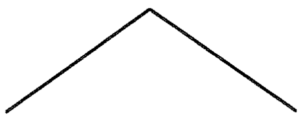

Figure 3

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71. The two figures are taken from E. Rubin, *Visuell Wahrgenommene Figuren*, Kopenhagen, 1921.

72. A brief account of the history of this movement can be found in V. Somenzi, "The 'Italian Operative School'", *Methodologia*, 1 (1987), pp. 59-66.

73. When the subjects consider the figure as a line or as an angle, we found some differences also in the movement of the eyeballs; see R. Beltrame, A. Berbenni, and G. Galassi, "Contribution to the studies of the movements of the eyeballs during optical perception by means of high speed motion picture photography", *Proceedings of the 7th International Congress on High-speed Photography*, edited by O. Helwich, Zurich, 1965, pp. 257-64.

74. A possible genesis of the linear perspective considered as a mental habit was discussed in R.Beltrame, *The Renaissance perspective. Birth of a cognitive fact*, Quaderni di *Methodologia*, 3, Roma 1996, 120 pp; also as CNUCE Report C97-24, last revision Nov. 1998, (both in Italian).

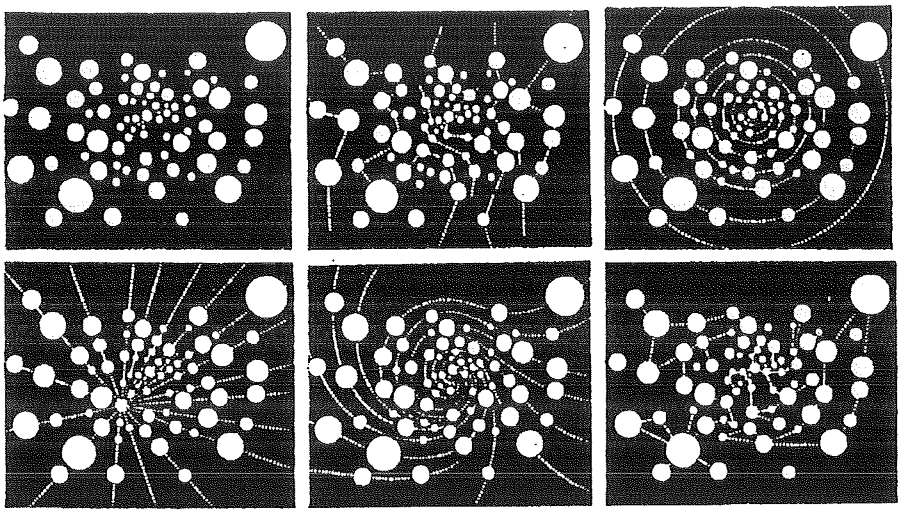

Figure 4

can be considered as being an isolated system. Here too the physical process that describes the actions of the environment on the biological system must be thought as being the projection of a path segment into a suitable subspace of the phase space, and this segment may be common to different paths. The same remark holds for the physical process by which we defined the mental thing that we assume to be the final result, and so the same consequences hold that we outlined below. However, we have here an intermediate activity, whose role is determinant to obtain the result.

The perceptive situations illustrated in Figure 4[75] propose a good example of the role of such an intermediate activity. We can easily verify that the white circles have the same diameter and the same reciprocal positions in all the six figures. The further lines suggest different perceptual organizations of the figure, and they seem to be quite necessary when we wish to obtain perceptual organizations that we can categorize as being ordered situations. In these cases we can reasonably assume the actions of the environment to be different, because the further lines assume great importance. Therefore an equality can result only by a comparison of the figures according to a different kind of criteria: the diameter of the circles and their reciprocal positions.

Mental categorization also participates to this second aspect when we consider the same thing in different ways: for instance, as cause or effect, as the same or another thing, as a part or a rest, and so on. Moreover, mental categorization participates to this second aspect because it plays an important role in characterizing mental attitudesas well. We can define a mental attitude as a particular way of operating, which can be characterized by the occurrence of certain mental constructions, usually mental categories, or by the frequency of their occurrence[76]. With this type of definition we can distinguish a great number of mental attitudes, and not only those to which historically a designation was given, like, for instance, esthetical or ethical attitudes. However, this characterization allows us to think of a mental attitude as being very similar to a constraint on mental activity, and we are led to the dynamics of our systems. Therefore, although we might mention many other situations like those that we discussed in this section, we prefer to discuss the activity flow, and its constraints.

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75. The figures were prepared by P. Parini for the exhibition "Mind and Image", Gallery of Modern Art, Bologna, 1978.

76. A certain number of mental attitudes were defined following the approach outlined here in S. Ceccato, "A Model of the Mind", *cit.*; and in R. Beltrame, "Perceptive Operations", *Thought and Language in operations*, I, 2 (1970), pp. 174-198.

The dynamics of mental activity and its constraints

In the previous sections we discussed the structure and the characters of a certain number of relevant mental facts. In this section we will focus on the flow of mental activity, and we will compare its dynamics with that of the physical processes. The dynamics of both mental and physical activities is a critical topic of the integration of cognitive sciences and neuroscience because, as we mentioned above, mental facts and activities require a definition, and definitions are neither true nor false: they are only less or more useful to do something else. The development of a theory is probably one of the main purposes in a scientific context, and the dynamics is an essential part of any theory. The dynamics is thus a critical test of the definition's usefulness, and we will start by briefly outlining the main differences that dynamics assume in a physical and a psychological description.

As we have seen, in a physical description the system dynamics can be optimally represented by a theory in which we systematically use the cause-effect relation, and in which we choose the things to consider as causes and effects in such a way that a bijective function holds between the causes and their effects. We recall that in this context the systems are the usual biological systems extended to a suitable part of their environment so that the enlarged physical system can be considered as being isolated. Environment actions thus become interactions between parts of the enlarged system, and we can completely predict the energy exchanges. Clearly, the total energy of the enlarged system is constant. As we discussed in a previous section, we can meet practical difficulties to fulfill these assumptions, mainly because of the difficulties in collecting the information needed to develop such an optimal theory for biological systems; but we have no conceptual difficulty. We will maintain these assumptions because they characterize a theory in which the differences between the physical and the psychological description become very sharp, and the problems acquire a clearer formulation. In this physical description the equations that describe the evolution of the system completely describe the dynamics of the system. We emphasize that different configurations of the values of the observables which characterize the state of the system lead to a different evolution, because we assumed that a bijective function of the causes onto the related effects holds in the reference theory. They thus describe the flow of the activity and the constraints on this flow.

A psychological description is conceptually more complicated, because we decided to define mental things through an injective function into physical processes which are characterized by a lower number of parameters than those which are necessary to give a physical description of our system's dynamics: that is, to predict the flow of physical activity. Mathematically, the function that we use to define mental things is not surjective, and the occurrence of mental things requires as a counterpart the occurrence of only a part of the physical activity that is necessary to describe optimally the dynamics of the physical system. This decision has a certain number of immediate consequences, and these consequences hold whenever we study the dynamics of things whose definition involves only a part of the processes that are necessary to predict a flow of the physical activity with the characteristics stated above, although these things are not mental things. This situation is rather frequent in psychology because much physical behavior, for instance movements, is defined in this way, and in the same way we usually define also the muscles' activity which is responsible for the utterance of the words and the sentences of our languages. Much of the human behavior is thus defined in this way.

In a system whose dynamics is represented in a phase space by paths that do not intersect, mental things are defined by projections, into certain subspaces of the phase space, of the paths that describe the dynamics of the system in the phase space. Since many path segments can share the same projection in a subspace of a phase space, the occurrence of what is defined by a projection is statistically more frequent than what is defined as a segment of a path in the phase space. In this picture a process which is represented by a segment of a path may occur only once or never in a given system. On the other hand, what is defined by a projection occurs whenever a path segment occurs which shares that projection. A mental thing can thus occur again during the life of the same subject, and this property is probably the main reason for defining mental things. The previous conclusion holds for everything that is defined through a one-to-one relation with a physical process that is represented geometrically by a projection of a path segment onto a subspace of the phase space, and in general it applies to everything whose definition involves only a part of the processes that are necessary to predict the flow of the physical activity. It thus holds for the occurrence of mental things, and for the occurrence of movements and utterances of a subject, which are defined in such a way. Since many path segments can share the same projection in a subspace of a phase space, the occurrence of what is defined by a projection can be obtained by performing the activity described by many path segments, that is by performing different physical activity. We thus find here a further source of explanations for the behavior that we usually ascribe to plasticity of the nervous system, besides the local changes in the biological system architecture, which we mentioned in discussing memory phenomena.

When we wish to predict the occurrence of mental things we have two possible strategies. We can correlate their occurrence with the occurrence of something else. In general, this correlation is not one-to-one[77], because a bijective function of the causes onto their effects can hold only between physical processes that are represented by segments of the same path in the phase space[78], but not when dealing with a projection of these path segments. The lack of this one-to-one correlation explains the difficulties involved in trying to obtain suitable definitions of mental things through binary relations, such as cause-effect, stimulus-response, or semantic relation. Furthermore, we expect that the correlation between mental things is often of the type many-to-many[79]. If in our theory we require the relation between the causes and their effects to be one-to-one, then we need further elements to single out the path and thus predict the following activity, but at the same time we predict further activity besides the activity that we used to define mental things. Furthermore, our predictions of the occurrence of mental things will be conditioned by the state of the system from which we start, because, starting from the current state of the system, the process must occur that carries the system to a state from which the next segment of path has as its projection the process used to define the mental fact or activity.

When for any reason we cannot use a representation of the dynamics of our system as paths that do not intersect in the phase space, the following general conclusions continue to hold. If we require that in our psychological theory the cause-effect relations are also one-to-one, then we must go to a physical description in which we have cause-effect relations with this character. The process whose occurrence is considered to cause the occurrence of the physical process that is the counterpart of a mental thing (and so, by definition, it causes the occurrence of the mental thing too) depends on the state of the system. Further physical processes occur, thus their occurrence too must be considered as being part of the effect, and these processes too depend on the state of the system.

In psychology a certain number of alternatives are historically used to treat the physical processes whose occurrence is considered to cause the occurrence of the physical process that we used to define a mental thing. In certain cases we introduce a faculty, such as the will-power, or the subject because we think of the subject as being able to perform physical and mental activity. In other cases we introduce motivation and drivers to explain the occurrence of certain mental facts or activities. Nonetheless, such a definition of motivation and drivers is not sufficient to ensure a one-to-one cause-effect relation with the characteristic stated above, because many paths can share the processes used to define a mental thing as their projection. Furthermore, motivation and drivers are usually defined through physical processes that are represented by projections of path segments into a suitable subspace of the phase space. We can thus have several motivations and drivers for the same mental thing, and we need further conditions to predict the occurrence of a motivation, and the occurrence of a mental thing. The state of the system would be sufficient to determine which motivation or driver occurs in a particular case, but the state of the system is rather difficult to individuate in a general theory, and we must be aware of this situation to avoid a *regressum ad infinitum* in the theory.

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77. We recall that it is a tautology to use the occurrence of the physical thing that we used to define a mental thing for predicting the occurrence of the mental thing.

78. The essential condition that the segments belong to the same path is equivalent in this picture to referring to the same system, and the knowledge of the path can be substituted by the knowledge of the state of the system at a certain instant of time, because the paths do not intersect.

79. When I worked in mechanical translation, I found an example of this situation in the so-called notional sphere: that is, in the relations network between the thing designated by single words. See, for instance, S. Ceccato Eds., *Linguistic Analysis and Programming for Mechanical Translation*, Gordon & Breach, New York 1961; and S. Ceccato Eds., "Mechanical Translation: the Correlational Solution", USAF Report RADC-TR, 1963

The path segment which occurs implies further physical processes besides the physical processes that we used to define mental things or motivations, and it is not so immediate to individuate in a psychological description the elements which are the counterpart of this further physical activity. In fact, a part of these further physical processes is often described as metabolic activity. The consequences are rather subtle, and they have not been studied much. For instance, we can find such consequences in clinics, as psychosomatic effects or diseases. This further physical activity is also essential to explain the occurrence of other, subsequent effects, and among these effects we can have mental facts. We may have thus a break in the prediction of a chain of mental facts, when we use correlation as well. The overall result is a theory in which the explanations prevail of single facts taken in isolation, and the correlation has a short time range.

As we saw at the beginning of this section, in a physical description of the system's behavior the equations that describe the paths in the phase space also describe the connection among the various segments of activity. They thus implicitly describe the constraints on the activity flow, and we do not need further elements to describe the dynamics of the system. On the other hand, when we take the viewpoint of psychology, a suitable theory of human behavior has to satisfy the common assumption that considers this behavior as being anomalous when we observe a flow of small and disconnected pieces of mental activity: that is, when the behavior has a severe lack of stability and of coherence. We also consider an excessively stereotypical behavior as being equally anomalous, and we impute it to a poor mental activity of the subjects, or, at least, to an excessive polarization of their mental activity. Thus a satisfactory description of systems to which we attribute a sophisticated intelligent behavior, like human beings, must be equally far from these two extremes. Since we decided to define mental things by using only a part of the physical activity which is necessary to describe the dynamics of the system, we may obtain this result by assuming the course of the mental activity to be constrained. In this way we may avoid psychological theories in which the behavior is too fragmented and disconnected, and, if the schemes of constraints are sufficiently rich and flexible, then we can also avoid theories in which the behavior would be too stereotyped.

We will distinguish two extreme situations in constraints: constraints which impose a span of activity that cannot be interrupted, and constraints which impose an activity that can be interrupted. We can find examples of the first type in procedural memory items whose execution cannot be interrupted, Since they become atomic and they acquire an on-off dynamics[80], they are not sufficient to constrain mental activities as thought and deductive reasoning. For this reason we have to introduce as constraints pieces of thought as well, and we assume that the subjects use them as paradigms when they perform mental activity. This second type of constraints clearly imposes an activity that can be interrupted. This dichothomy is very schematic, because we can easily show intermediate situations. For instance, the action of procedural memory items can be accompanied by an activity that we can describe as having the function to monitor the state of the system, and to stop the driving function of the procedural memory item when the state of the system does not match certain conditions, or the parameters that characterize it are outside a certain range[81]. Walking is a good example of this situation, and is often presented as an example that supports a hierarchical scheme of motor control in neurophysiology[82]: that is, in the physical description of this behavior. Walking is an activity in which the details of the control of the muscles that are necessary to perform the activity do not require a conscious intervention of the subject, who can freely think during walking. From this point of view walking can be ascribed to the iteration of a procedural memory item. However, when an obstacle, or some other cause, unbalanc-

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80. The property that the span of activity cannot be interrupted allows us to define and distinguish different items of procedural memory; that is, an item of procedural memory is the span of activity that is induced by memory and cannot be interrupted. However, the dynamics of the procedural memory can change the items, and we expect an additive composition of items to hold only under extremely particular conditions.

81. We can think of such a kind of procedural memory items either as a single process of suitable complexity, or as two or more concurrent processes. As mentioned above, we can freely choose one or the other scheme, however in biological systems we have some problems. The scheme of concurrent processes is really useful when no interaction affects the parallel processes between two subsequent synchronization points. When, like in mammals, we have endocrine and immunological systems that are highly pervasive, we must carefully check that a decomposition in concurrent processes satisfies the requirement indicated above.

82. See, for instance the part devoted to the control of movement in E.R. Kandel, J.H. Schwartz, and T.M. Jessel, *Principles of Neural Science*, 3rd edition, Elsevier, 1991, pp. 533 ff.

es the body more than a certain amount, we can observe a shift to an activity that corrects the posture, so that it often avoids a fall, and that has the character of a conscious activity.

The main source of procedural memory items that cannot be interrupted is training. The classical Pavlovian conditioning is a way of realizing this training without necessarily introducing a mental activity, because it is usually described as follows. An indifferent cue, for instance a flashing light, when properly paired with an unconditioned stimulus (US), for instance a shock, can be trained to elicit some of the consequences of the US in the form of a conditioned response (CR), for instance various indices of fear, and so the original indifferent cue becomes a conditioned stimulus (CS)[83]. Another training method involves a mental activity, and is usually described as the repetition of a voluntary activity until the subject becomes able to perform the activity without driving it consciously.

We will outline some differences between these two ways, and a common problem. In Pavlovian conditioning we have a new stimulus that elicits the same response of the unconditioned stimulus. So, we only have a new correlation among facts. Mathematically, the mapping of the CRs into the CSs is not a single value mapping, and this means that we cannot infer unambiguously the stimulus from the response. This fact prevents us from using, as a general strategy, stimulus-response relations of this kind to define a mental thing: for instance to define a mental thing as being the stimulus in relation to a physical thing that we consider as being a response. Since an injective function fails, we do not have a suitable definition of the mental thing. Voluntary actions, for instance voluntary movements, are typically thought of as having a goal: that is, their occurrence is explained by a final cause. However, a final cause is not useful to test predictions about the occurrence of something, and an efficient cause is required. In a psychological description the efficient cause of voluntary actions is thus the subject who performs them. In a physical description this solution cannot be accepted, because, by definition, the change must be induced by a physical thing different from the thing that changes, and we meet a further case of a break in isomorphism between the physical and the psychological approach to our system's dynamics.

A common problem arises when we compare the way of defining an item of procedural memory with the characters of the physical description that were recalled at the beginning of this section. The problems arise again from the consequences of defining a procedural memory item through an injective function into a physical process which is not a segment of the paths that describe the system's dynamics, but a projection of this segment onto a subspace of the phase space. A first set of consequences arises because many paths can share the projection. The physical processes that are the counterpart of the procedural memory item can thus occur in different conditions, and in different specimens too, of the same biological system. This is a very good reason to define an item of procedural memory in a psychological description. If we used a path segment to define an item of procedural memory, rather than the projection of a path segment, then the item so defined cannot occur again in the life of the same system. Note that the path segments which share a projection in a given subspace are determined by the dynamics of the enlarged system: their individuation is thus matter of experiments.

A second set of consequences arises once again because in the theory we do not have a unique cause of the processes that are the counterpart of a procedural memory item[84]. An item of procedural memory thus explains the connection between the activities that constitute a certain fact, but the conditions of its occurrence are usually introduced in the psychological description as motivations or drivers, and we must be aware of the facts that we discussed above. Typically, we have several motivations and drivers for the same procedural memory item, and we would need further conditions to predict the occurrence

83. The conditioned stimulus theory has to explain the situation described in the text, to which we refer here as Experiment 1, and these further experimental results. Experiment 2 points out that if two equally salient cues, for instance a flashing light (CS1) and a tone (CS2), appear simultaneously during conditioning trials before the shock (US) occurs, then each of the cues can separately elicit a fearful reaction (CR) on recall trials. Experiment 3 is constructed by performing Experiment 1 before Experiment 2. When the tone (CS2) is presented on recall trials, it does not elicit a fear reaction (CR). Experiment 4 is like Experiment 3, but the US is varied in the compound trials. For example, the US1 which follows the light (CS1) is a prescribed shock level, and the US2 which follows the compound light and tone (CS1+CS2) is a sufficiently different shock level. If US1<US2, then the tone elicits a fear reaction, whereas if US1>US2, the tone elicits a relief reaction. See, for instance, S. Grossberg, "How Does a Brain Build a Cognitive Code", *Psych. Rev.*, 87 (1980), pp. 1-51, with the related bibliography.

84. That is, a process whose occurrence is in a one-to-one relation with the occurrence of the procedural memory item.

of a procedural memory item. The state of the system is sufficient to determine which motivation or driver occurs in a particular case, but these further conditions are rather difficult to individuate exhaustively in a general theory. Therefore, the relation between the occurrence of certain motivations or drivers and the subsequent occurrence of certain procedural memory items, can be safely interpreted only as a correlation between the two orders of facts; a one-to-one cause-effect relation is very improbable, and must be proved in each case.

The picture on which we grounded the previous discussion is also useful to describe an aspect of procedural memory dynamics. The requirement that the occurrence of an item of procedural memory cannot be interrupted, strongly limits the possibility of adding two or more previous items of a procedural memory to obtain a new item. The result must have as a counterpart in the physical description a projection of a segment of a path that describes the system dynamics in the phase space[85]. This condition must hold, otherwise we would violate the condition that physical processes, which we define as the counterparts of the new item, flow without interruption. Verifying this condition entails knowing the mutual positions of the projections that we think to be joined, and this knowledge follows only from experiments, because the configuration of the paths in the phase space depends on the physical architecture of the enlarged system. The condition that we have just pointed out may explain a phenomenological observation. When we learn to execute very fluently a series of complex movements, such as in athletics or in playing a musical instrument, the history by which we reach the skill may become significant. Let the first part of the planned movement have as a counterpart some physical processes, and let these physical processes, in the conditions of the movement's occurrence, belong to a path whose continuation does not contain the processes that are the counterpart of the continuation of the planned movement. Clearly the planned movement cannot occur in these conditions, and we can only try to change the conditions under which to execute the movement, or to plan the details of the movement differently. Analogous situations can be observed in the strategies of medical rehabilitation, particularly when they significantly involve the plasticity of the nervous system. Therefore, the growth of procedural memory seems to be a rather complex process, which cannot be reduced to a linear composition law, and which is a further source of nonlinearities in the theory.

The content of the paradigms too has several sources. One source can be found in the constitutive characters of the different mental things that are defined in the cultural framework of a certain individual, or of a certain group of individuals. However, subjects use these constitutive characters certainly as a paradigm only in two situations: when they are concerned with the definition of a mental thing, that is when they are dealing with concepts or notions, and when they recognize an object or a fact. The last situation certainly occurs when a subject replies to questions like "Is that thing a dog?". In other situations we are not forced to assume that subjects use paradigms to explain their behavior. For instance, we can assume the perceptive activity as being the direct promoter of the friendly behavior that we observe in babies when they perceive the face of their mother, or her voice. Therefore we may have a situation that shares certain characters of procedural memory items.

A further great source of paradigms is in the consequences that we expect from having done certain activities. A large class of such paradigms arises when we assume that certain objects have a certain role in certain processes, and that some facts follow from the occurrence of a certain other fact. For instance we assume as a paradigm that fire has the subject's role in an activity, burning, which transforms wood into ash. Note that, when the occurrence of certain results and transformations is thought to be independent of our mental activity, as in the above example, we must check by observations and experiments whether the paradigms are fulfilled. We found another example when we discussed conscious memories: when a subject categorizes a mental activity as a repetition of one that occurred to him in the past, the two activities are consequently considered to be equal. If some differences are found on a subsequent check, then they are usually explained; thus confirming the presence of a paradigm.

Another source of paradigms is in the constraints on mental categorization, and this fact is particularly evident in a scientific context. The systematic introduction of strict constraints is here a conse-

85. We note that by definition we do not use the scheme of concurrent processes when we represent the dynamics of a physical system by means of paths in a phase space.

quence of the repeatability requirement, because mental activity has a private character. Thus, in scientific activity we usually bind to the occurrence of specific technical procedures the use of the mental categories that occur in theories and in the description of experiments. For instance, we must use the techniques of geodesy and topography to assert that we measured again the distance between the same two points and their difference in height. 'Same' and 'other' are mental categories, and their occurrence uniquely requires that someone carries out the related mental activity. However, we decide to use 'same' in this context only when certain technical procedures are well suited, otherwise the categorization will be considered to be incorrect, rather than the category. We do not always succeed in finding suitable technical procedures to which a categorization can be bound. An example is the assertion that a certain volume contains the same physical particles that it had at a past instant of time, because we do not succeed in identify the single particle in quantum mechanics. We then change the thing that we categorize as being the same, and we develop theories where the datum is only the number of particles of a certain type that occupy a given volume at a certain instant of time. Then it is matter of mathematical technology to use this statement directly or to use equivalent mathematical transformations[86].

A compliant use of mental categories in scientific theories and in the description of scientific experiments, allows us to infer the occurrence of mental categorization, which, being a private activity, cannot be directly observed. In fact, we infer that a mental categorization occurs from the occurrence of the technical procedures to which we bound the categorization. We thus understand why it is considered to be so important to find suitable technical procedures to which a categorization is constrained since in this way we ensure that the repeatability requirement holds. Furthermore, we always assume that the related technical procedures were correctly applied when we use the categories in a scientific context, and we expect the consequences that follow from their correct application. For these reasons, when we mention a category in a scientific context, we also refer to the procedure that constrains its use in the current context. Low awareness of these facts often causes bad philosophical statements.

We often constrain the categorization to characters of the things that we categorize, which are described by quantities that vary continuously. In these situations we usually constrain the categorization to certain threshold values of these quantities. We can always consider that the categorization is a qualitative difference, but only after categorization do the things that we categorized support two different points of view. We can consider them as things that were either categorized in a certain way or not, and so we have a qualitative difference. We can consider them as having the characters only to which we constrained the categorization, and from this point of view we have a continuous change in these characters. We thus have or do not have a qualitative difference depending on the viewpoint that we adopted, and we cannot expect that, before the categorization, the things that we categorized have this qualitative difference from the things that we did not categorize in that way. Categorization is an activity performed by the observer, who often considers the result as being a property of the thing that he categorized. The characterization of a behavior as being intelligent, which we discussed above, is a good example of such a situation. It confirms that categorization introduces a distinction among things, in our case between intelligent and not intelligent things. However, we must be aware that such a type of distinction depends on the categorization and its constraints, that is on our cultural schemes, because we can easily find a continuity when we look at the conditions to which the categorization is constrained. Cerebral death offers a further example, and in this case we link deep practical consequences to the mental categorization. Low awareness of this fact may give rise to a rather naive philosophical realism[87].

[86]. A common strategy has two steps. We firstly write the mathematical relations that should hold among physical particles that can be distinguished. In a second step we impose the conditions that must be satisfied by the mathematical description when we exchange two or more particles. In such a kind of situation it would be a good policy to avoid the use of terms such as 'exchange force' or 'exchange interaction', which may be misleading.

[87]. Despite the analogy in constraining mental categorization, the physical theories that contain mental categories as explanatory elements are not completely equal to the psychological theories. We must remember the great difference discussed at the beginning of the paper: in psychology a mental scheme is used where the subject is cause of its changes, and in physical theories a mental scheme is used where the changes on one thing are always caused by another thing. Therefore, when in a theory we introduce as a general term something that is defined as being the cause of something else (for instance, the force as being the cause of an acceleration), we also consider that the related mental scheme holds from physics, or from psychology.

A more general source, which is analogous to the constraints on mental categorization, is the conditions under which a mental activity has to be performed. For instance, the conditions of light, distance, etc., under which a perceptive result has to be attained to have a recognition of the objects that we consider to be satisfactory. The failure of these conditions is often signalled by saying that the object appears with a certain shape or colors, instead of saying that the object has certain shape or colors.

Paradigms may raise an ambiguity, because the activity of assuming a certain fact as a paradigm, which is a mental categorization, may be made either by the observed subject, or by the observer, or by both. When the observed subject assumes a certain fact as a paradigm, usually we have to identify further elements to explain the occurrence of the next activity, because typically we can predict more than one alternative for the reasons discussed above. In the second case we have a theorist who assumes a certain behavior as a paradigm, and who declares that the observed behavior is normal when it is equal to the behavior assumed as a paradigm, or who explains the observed differences. However, when we decide to explain why the observed subject behaves in the observed way, we must use other elements, because we also have to explain why the observed subject has the behavior that was declared to be normal. When both the observer and the observed subject assume a fact as a paradigm, we have more articulated situations, in which the paradigms may or may not be the same. The situation that we depicted can occur every time we deal with a theory of mental activity. Low awareness of these points leads to fruitless discussions and to inconsistencies in theories. Although these points are very critical, in this paper the context will generally decide whether the mental categorization is made by the observer or by the observed subject. If we indicated each time the alternative with which we are dealing, the paper would become difficult to read, and we hope the context will be sufficiently clear for a reader who is now aware of the problem.

Paradigms differ above all from procedural memory items, since we assumed that the mental activity which constitutes the paradigm can be interrupted, and this property has two different realizations. When the paradigm is used by an observer, he accepts to observe that the activity described by the paradigm does not flow continuously. When the paradigm is used by the observed subject, we accept that he can interrupt the activity described by the paradigm. Both the assumptions that the activity described by paradigms tolerate interruptions, and at which point we can observe the interruptions of activity, are part of the definition of a paradigm.

The activity described by paradigms tolerates interruptions, its relation to the physical description of the system's behavior is thus significantly different from that of the procedural memory items. The flow of a physical process is described as continuous, because situations in which the values of the observable do not change for a certain interval of time are described as a particular process. Thus a physical process can be thought of geometrically as a continuous line in a space having a suitable number of dimensions[88]. The items of procedural memory have the same character, and, from this point of view, they are quite similar to a physical process. The paradigms do not, and, when we relate the occurrence of the activity described by a paradigm with the physical description, we expect situations of the following type. We have the occurrence of two physical processes which are the counterpart of the activity described by the paradigm before and after an interruption, between them we have the occurrence of another physical process whose counterpart does not belong to the activity described by that paradigm. Therefore, the strong constraints do not hold for paradigms, which we have seen to hold for the items of the procedural memory because they cannot be interrupted; although these constraints continue to hold for the parts of a paradigm's contents in which no interruption is admitted. The result is a more complex dynamics, because the activity which follows an interruption may lead to the further activity described by the paradigm, or to assuming a different paradigm. Since all the activity described by a paradigm does not necessarily occur, a paradigm merely predicts an activity, but it does not prescribe it. Paradigms thus cover a wide range of possibilities, because their effect can be quite similar to, or very different from those of a procedural memory item, and this fact depends on the number and the extent of the possible interruptions. Since paradigms only predict a mental activity, the mental activity can occur according to a paradigm and the language usually reflects this agreement by chiefly using

88. When our system's dynamics is described by paths that do not intersect in the phase space, this space is either the phase space, or a subspace of the phase space.

direct designations and the indicative mood of the verbs, but we equally accept and speak of the occurrence of an activity that does not follow a paradigm completely, although we are led to explain the differences[89].

The physical processes that we define as being the counterpart of the contents of a paradigm cannot be segments of a path that represents the system dynamics in the phase space, otherwise we would contradict ourselves in assuming that we can drop the activity which is prescribed by a paradigm after an interruption. Then, in defining paradigms, we must use processes that have, as a geometrical representation, projections of path segments into suitable subspaces of the phase space. The same consequences thus follow that we found to follow from this fact for procedural memory items, and in general for mental activity. The psychological description will thus contain motivations and drivers to explain why a certain paradigm is used by a subject in a certain moment. The same paradigm can have different motivations, whose occurrence depends on the current physical state of the enlarged system. The relation between the occurrence of certain motivations or drivers and the assumption of certain paradigms, can be safely interpreted only as a correlation between the two orders of facts. A one-to-one cause-effect relation forces us to going back to the physical description, it requires the knowledge of further physical facts, and the effect includes other physical facts besides the physical facts that we used to define the paradigm and its motivation.

We saw that the items of procedural memory have a dynamics because they result from learning. The paradigms too have a dynamics, because, from a psychological viewpoint, they can be identified with a conspicuous part of the experience and culture of the subjects. So, they too depend on learning, and they have a fast evolution, at least in certain periods of the subject's life. Since paradigms refer to an activity that can be interrupted, we do not have the strong restrictions that we have when we try to obtain new procedural memory items by combining existing ones. Pieces of paradigms between two interruptions can be freely joined to constitute new, more complex paradigms, and this possibility shows that the new paradigms frequently arise with strong relations with the previous ones. The system of paradigms thus grows like an organism, while the system of procedural memory items grows only by simple addition of new items[90]. Some elementary examples will highlight the kinds of situations that can occur during the development and the evolution of the paradigms.

Let us have a color difference that we localize in the surrounding space, and that we think of as characterizing a physical object. Then we usually think that there is also a tactile difference in the same place, and we expect to find it. For instance, we think of our hand reaching a place, and the change in tactile perception[91]. However, we do not expect to find a tactile difference where we do not perceive any visual difference. In fact it is mandatory to mark clearly the presence of a glass door that is made of a single, transparent sheet, otherwise someone will walk into it.

We can find another elementary example in an already classical experiment in psychology of visual perception. In mono-ocular vision, and by suitably masking the context, the subjects report seeing experimental situations like that in Figure 5 as being like that of the photograph in Figure 6[92]. That is, they interpret the mutual positions of the objects as being in an order which is the reverse of the order illustrated in Figure 5. We can explain this result by assuming that subjects think of all the squares and the cards to be complete: that is, without the cuts that we see in Figure 5. Therefore we can explain that the subjects do not think of the situation as that illustrated in Figure 5, although it might be possible,

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89. When a subject explain these difference we can clearly infer that he used a paradigm.

90. The relations between the items of procedural memory is thus a criterion of analysis and description that is used by theorists, and not by the subject who uses the procedural memory item.

91. We can obtain illusive effects by synchronizing visual, hearing, tactile, and smell stimuli according to the patterns that a person expects, although they arise from different physical situations than the usual ones. This is the leading idea of virtual reality; where the term 'virtual' highlights that the sources of the stimuli are different from those we assumed as a paradigm for these stimulations.

92. For experiments of this type see: J.J. Gibson, *Perception of the visual world*, Boston, Hampton, 1950; W.H. Ittelson, "Size as a cue to distance: static localization", *American Journal of Psychology*, 64, 1951, pp. 54-67; W.H. Ittelson, "The constancies in perceptual theory", *Psych. Rev.*, 58, 1951, pp. 285-294; A. Dinnerstein, W. Epstein, "The influence of assumed size on apparent distance", *American Journal of Psychology*, 76, 1963, pp. 257-265; L. Ancona, *The dynamics of the perception*, Mondadori, Milano, 1970, pp. 53-70 (in Italian), from which the figures were taken; J.E. Hochberg, *Perception*, 2nd Ed., New York, Prentice-Hall, 1978.

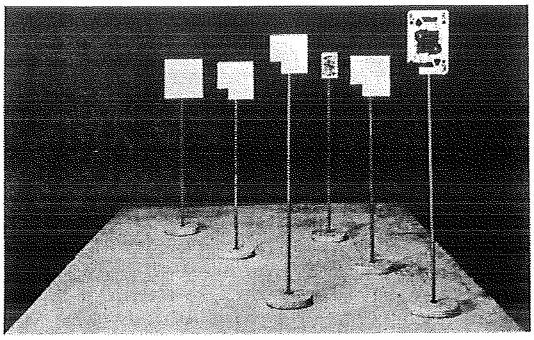

Figure 5

because it is quite improbable on the basis of their experience. After thinking the objects in mutual positions as those illustrated in Figure 6, the subjects see them as having a size which depends on these mutual positions, and on the visual angle from which they see each object. This angle, in fact, settles a relation between the size and the distance of the object, and this relation describes a constraint on mental activity that results from learning[93].

A television screen is a two-dimensional surface, but we see usually the rooms and the objects that are presented on it as being three-dimensional. The camera lens gives a result that is usually very near to a representation of the room and the objects on a plane perpendicular to the optical axis of the lens, and by following the rules of linear perspective. Since the Renaissance, we have been accustomed to seeing things that are represented in perspective as being three-dimensional; and the great diffusion, in our time, of images that are produced in this way by optical systems has confirmed this habit. Furthermore, in watching television we also became accustomed to assuming the position of the camera as our observation point, and the axis of the lens as the principal axis of the vision field. These assumptions, and the movements of the camera when filming, reinforce the tendency to think of the things represented as being three-dimensional, because we experience effects that are similar to stereokinetic ones. This is a good example of a common situation: an acquired habit leads us to performing a mental activity with a higher probability than other possible ones[94], because, as we noted above, we usually see a perspective as a two-dimensional pattern when we are drawing it.

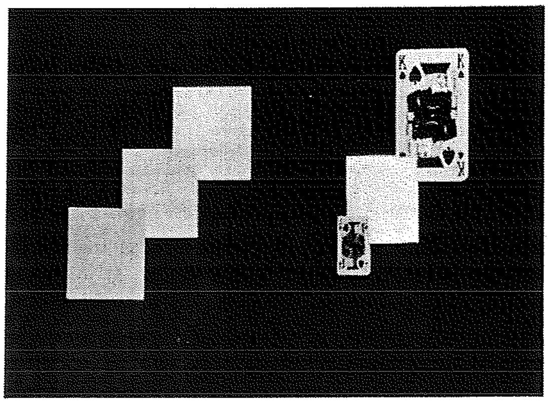

Figure 6

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93. A good review of experimental results can be found in A. Yonas, C.E. Granrud, "The development of sensitivity to kinetic, binocular and pictorial depth information in human infants", in D. Ingle, D. Lee, M. Jeannerod (Eds.), *Brain Mechanisms and Spatial Vision*, Amsterdam, Martinus Nijhoff Press, 1984.

94. Brunelleschi in his first experiment, which marks the beginning of modern perspective, used the acquired habits of his contemporaries in a very subtle way to induce the observer to give a three-dimensional organization to the perspective pattern. This aspect of Brunelleschi's works on perspective was discussed in great detail in R. Beltrame, *The Renaissance perspective. Birth of a cognitive fact, cit.* (in Italian).

The examples discussed above also show some directions along which paradigms grow. Very early in our life we get accustomed to adding a spatial localization to the color differences that we perceive in our visual field, and to think that we shall also find a tactile difference in the same place. This pattern of activities is learned as part of the coordination of the visual, motor, and tactile activity that we need to hold an object. Nevertheless, this simple paradigm becomes conditioned by other elements when our experience grows. For instance we do not add a tactile difference when the color differences concern something that we thought of as a plane figure, like a book illustration; and so on. The images on a television screen immediately give an example of the ever increasing sophistication of the constraints' scheme. We agree to add a tactile difference where before we locate a visual difference, but our paradigm now distinguishes between the constraints that concern the objects represented on the screen, and the constraints, which refer to objects, like those of the television set, that belong to same environment as our body. If, for instance, two of the represented objects collide, then we expect to see the usual consequences of a collision between two physical objects. However, we do not move from our chair when a car is represented on the screen as coming up to us. Such behavior requires a high level of thought articulation. The world of our experiences and of our knowledge must be applied to the situations that are represented on the screen; but, at the same time, we must expect that the represented actions have very different consequences on us and on the represented objects. Yet these few examples confirm the essential characters of the paradigms: they result from learning, and they depend both on the history of the particular individuals, and on the history of their cultural environment. The growth of the subject's experience and knowledge either involve the extension of the paradigms to new fields, or will increase the number of elements that the subject makes the occurrence of a fact depend on: that is, he requires a richer and more articulated pattern of conditions to expect the occurrence of a fact[95].

Since paradigms often describe consequences that concern our body and its relations with the objects of our environment, and these consequences frequently have a strong impact on our actions and behavior, we usually choose as paradigm situations that occur with reasonable frequency, or that are critical for our behavior. Therefore, when the occurrence of the prescribed facts fails:

- we can add new conditioning elements to the scheme, which explain the failure, and we use the extended scheme as a new paradigm;
- we can decide not to pursue the mental activity that we have just carried out, and to substitute it with a mental activity from which the occurred consequences follow; for instance, we usually cease to consider something as being nearer to us than another thing, when further tests do not confirm the result of our perception, and we reverse the categorization of the two things;
- we can cease to consider a mental activity as being predictive of another, and the modified scheme becomes the new paradigm;

so, we can change our choices, but only when we are forced by very strong reasons. Since we use the paradigms in deductive reasoning to predict facts of practical relevance, for instance consequences of our body's interaction with other physical things, and since from a contradiction we can deduce both a proposition and the opposite, the presence of contradictions in the scheme of the paradigms would destroy the practical relevance of the deductions. For these reasons we require the paradigms' scheme to be free of contradictions.

This last aspect of the paradigms' scheme allows us to avoid any ontological dualism between physical and mental things, that we might inherit from the history of philosophy, and that will destroy any program of integrating neuroscience and cognitive sciences. The main aspect that the ontological dualism should explain can be illustrated by the following simple example. We accept that fire occurs as a cognitive fact only if we have the related cognitive activity, and we still accept that this cognitive activity will occur only when we have someone who performs it. Nonetheless we equally accept that the fire burns a piece of wood and transforms the wood into ash, with no dependence on someone's thinking of these facts. That is, the occurrence of these transformations can be neither forced, nor forbidden only

95. The increased number of conditions which an individual requires to be fulfilled in order to expect a fact can explain why aged and experienced individuals are more skeptical about the possibility to obtain a certain result. The same fact can contribute to increasing their reaction time, because the individual will wait for the occurrence of more conditions before starting the reaction.

by the mental activity of someone who thinks that they have or do not have to occur. After having thought of fire as being the subject of burning activity and of the related consequences, we must ascribe to the fire the activity of burning a piece of wood, and the related transformation of the wood into ash. We cannot ascribe it to another subject, for instance who is performing the mental activity of thinking that the fire burns a piece of wood, otherwise we would contradict ourselves, and we decide not to contradict ourselves because we want to make inferences and logical deductions that concern physical facts whose occurrence may also concern our survival. Therefore it is not necessary to introduce two ontological different principles (one for the world of physical things, and the other for the world of mental facts) in order to explain why the occurrence of a physical process is independent of anyone who thinks that this process has to occur or it does not. Note that this independence follows from two decisions: the decision to place ourselves in the framework of a knowledge system, and the decision to have a knowledge system without contradictions. The first decision also implies that we use paradigms as discussed above, with their source and dynamics. In particular, we use paradigms when we think of physical objects, their interactions, and the consequences of these interactions. The second decision is motivated by the requirement that inferences and logical deductions do not admit both a proposition and its negation.

The dynamics that we discussed above is tailored to the individuals, in particular the paradigms discussed above are the paradigms that the individuals use, and they reflect the personal history and the biological architecture of each individual, with any pathological aspects as well. When we are interested in a more general theory which encompasses different individuals, the physical description can continue to use the theory that we decided to use as the reference theory. Since a system of this theory includes the biological system and a part of its environment such that the enlarged system can be considered as being isolated, in a general theory we must consider a biological system which has enough characteristics to encompass the individual differences, and the environment must be consequently enlarged. When the dynamics can be represented in a phase space by paths that do not intersect, the evolution of different individuals will be represented by different paths, a one-to-one relation will hold between each path and a particular set of condition, and the general dynamics will be represented by the possible paths in the phase space.

When we decide to develop an analogous general theory of mental activity we clearly need further paradigms, which are different from the paradigms used by the subjects to perform their mental activity. These new paradigms are used by the theorist, and they must allow to explain and predict the difference that we observe in the paradigms assumed by the different individuals in doing their mental activity. Simplicity is the main characteristics of this new type of paradigm. On the other hand, in the paradigms used by individual subjects, the frequency of their occurrence prevails, or their relevance for the subject's life. The dynamics of these new paradigms is thus very different. Furthermore in a general theory we see the assumption of paradigms in doing mental activity as an object of investigation, and we usually interpret its consequences as a correlation between the occurrences of mental activities. We thus find a justification to consider the assumption of paradigms in doing mental activity as a constraint to the flow of mental activity; a point of view that we have used extensively in this paper.

The main conclusion is however that the theory of the occurrence of physical facts is not isomorphic with the theory of the occurrence of mental facts. As we have seen, this conclusion follows because the conditions, that we require to hold in physics to apply a cause-effect relation, are not compatible with the analogous conditions that we require to hold in psychology. So, we cannot identify the dynamics of the mental facts and activities with the dynamics of the physical processes that occur in the system that we consider as performing the mental activity, and we cannot assume a reductionistic position as a philosophical position. However, the most far reaching consequences follow from the decision of defining mental facts and activities by using only a part of the physical process that we must introduce to obtain a satisfactory physical description of the behavior of our systems. As we have seen, we can derive from this decision the theoretical possibility that a mental fact or activity will occur again in the same subject, or that it can be identical in different subjects: that is, in system that did not have the same evolution. We thus showed a strong reason for defining mental things, and the root of their possible intersubjective character. We also showed that only correlation can be set between the occurrence of mental facts and activities, and that the correlation has an essential, probabilistic character. So, we must go back to the physical description, if we wish to explain the occurrence of the mental facts and activities by means of a one-to-one relation between the causes and their effects, and this is another strong reason to refuse a reductionistic position. We also showed that the occurrence of a mental fact or activity is always accompanied by a further physical activity besides that we used to define the mental fact or activity, and that this further physical activity will depend on the current state of the system which is doing the mental activity. Since the subsequent physical activity shall depend also on this further physical activity, we need the physical description to predict the flow of the mental activity in a deterministic way. We must thus develop both the dynamics of the physical activity and that of the mental activity. furthermore, since the two dynamics are essentially different, we cannot mix elements that belong to the physical description with elements that belong to the description of psychology.