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T-pattern analysis for the study of temporal structure of animal and human behavior: A comprehensive review

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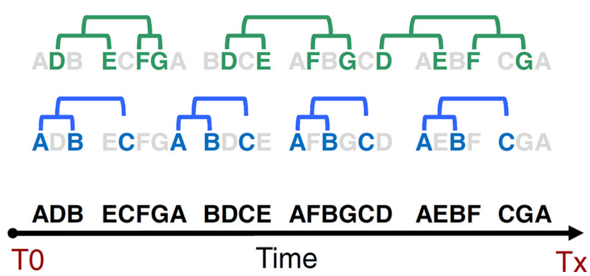
HIGHLIGHTS

- T-pattern analysis is a multivariate approach for the detection of the temporal structure of behavior.
- By means of T-pattern analysis recurring sequences of behavioral events can be detected and described.
- T-pattern analysis can be applied to the study of the temporal characteristics of behavior in different species from rodents to human beings.
- Background for researchers who intend to employ such a refined multivariate approach to the study of behavior is given.

GRAPHICAL ABSTRACT

Short string of 25 hypothetical events (black letters) occurring in a given time window (T0–TX). Albeit two different sequences of events (occurring four and three times, respectively) are present, the detection of such sequences is not an easy task if only the bottom row is observed. On the contrary, if the "extraneous" events are removed the two sequences A–B–C and D–E–F–G become evident. Such an example shows how easy it can be to ignore something we have before our very eyes.



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ABSTRACT

A basic tenet in the realm of modern behavioral sciences is that behavior consists of patterns in time. For this reason, investigations of behavior deal with sequences that are not easily perceivable by the unaided observer. This problem calls for improved means of detection, data handling and analysis. This review focuses on the analysis of the temporal structure of behavior carried out by means of a multivariate approach known as T-pattern analysis. Using this technique, recurring sequences of behavioral events, usually hard to detect, can be unveiled and carefully described. T-pattern analysis has been successfully applied in the study of various aspects of human or animal behavior such as behavioral modifications in neuro-psychiatric diseases, route-tracing stereotypy in mice, interaction between human subjects and animal or artificial agents, hormonal–behavioral interactions, patterns of behavior associated with emesis and, in our laboratories, exploration and anxiety-related behaviors in rodents. After describing the theory

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and concepts of T-pattern analysis, this review will focus on the application of the analysis to the study of the temporal characteristics of behavior in different species from rodents to human beings. This work could represent a useful background for researchers who intend to employ such a refined multivariate approach to the study of behavior.

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1. Introduction

Fourth century BC. Hellenic philosophers, such as Plato and Aristotle, theorized that human governments were characterized by a cyclic evolution of events, the so called "anacyclosis", a concept largely reprised also by the historian Polybius (Waterfield, 2010). Actually, more than two thousand years after, various aspects essentially consistent with the idea of repetition of events in time can be found in the thought of intellectuals such as Machiavelli (Mansfield and Tarcov, 1998), Vico (Goddard Bergin and Fisch, 2011) or Nietzsche (Nauckhoff and Del Caro, 2001), to name a few. It is evident that, through centuries of human thinking, the idea of the recurrence of events in time has a very long and rooted history.

Interesting topics of discussion arise when, beside the succession of governments and other "macro" events, as debated by philosophers and historians, the concepts of temporal patterns and recurrence of events are applied to the scientific study of human or animal behavior. A first obvious question could be, simply, if repeated patterns of events exist in human or animal behavior. An affirmative answer should surprise no one, in line with the modern view of biological phenomena, as clearly expressed by the Nobel Prize winner Francis Crick: "*Another key feature of biology is the existence of many identical examples of complex structures*" (Crick, 1988). Also, it is essential to consider the concrete possibility to study, from a scientific perspective, these repeated behavioral sequences and, last but not least, their putative role in terms of the resulting behavioral organization. Actually, from the perspective of the behavioral scientist, the possibility that the behavior of a subject does encompass a number of repeated sequences of acts may represent the essential substrate for the existence of a habit. Indeed, as underlined by Graybiel (2008), a behavior is defined as "habitual" when it occurs repeatedly over the course of time. Such a repeated occurrence of behaviors can become remarkably fixed. An intriguing neurophysiological research line concerns the identification of the putative neural substrate(s) linked with organization of these repeated patterns of behavior. Important evidences indicate that various circuits connecting the neocortex and regions of the basal ganglia may embody the anatomic–functional network underlying the control of repetitive behaviors. Coherently, anomalies in basal ganglia circuitry represent a critical aspect shared by numerous illnesses characterized by the abnormal presence of repetitive behaviors, such as Huntington's disease, Tourette's syndrome or obsessive compulsive disorder, among others (Graybiel, 2008). However, independently from their physiological or pathological nature, and independently from the performing subject, the detection of a repeated sequence of behavioral acts, may be a difficult task. Three critical issues determine how easily a sequence of behavioral events can be perceived/noticed by an observer: first of all, the *order* of each event, second, the *frequency* of the comprehensive sequence (namely, how many times it occurs) and, finally, the occurrence, within the sequence, of behavioral events irrelevant to the sequence itself. For instance, during a meal, the sequence of acts that a person must perform to consume a dish and/or a glass of wine can be easily detected because (1) the behaviors are relatively invariant in their order, (2) the whole resulting sequence is quite frequent, and (3) the progression of events within the sequence is rarely interrupted by the occurrence of other events. On the contrary, if a succession of behavioral events is infrequent and/or if a number of "extraneous" events occur, then it may be extremely difficult to perceive the presence of a given sequence. To better clarify such an aspect, the following example may be enlightening. Fig. 1a shows a short string of hypothetical events (black letters) occurring in a given time window (T0–TX). Two different sequences of events, occurring five and four times respectively, are present.

The detection of such sequences is not an easy task by observing only Fig. 1a. The reason is that, on the basis of the three aspects mentioned above, both the sequences: (1) always encompass events in an identical order and (2) are repeated various times; nonetheless, the third requirement is missing because several "extraneous" events occur between the sequences and within each sequence. As

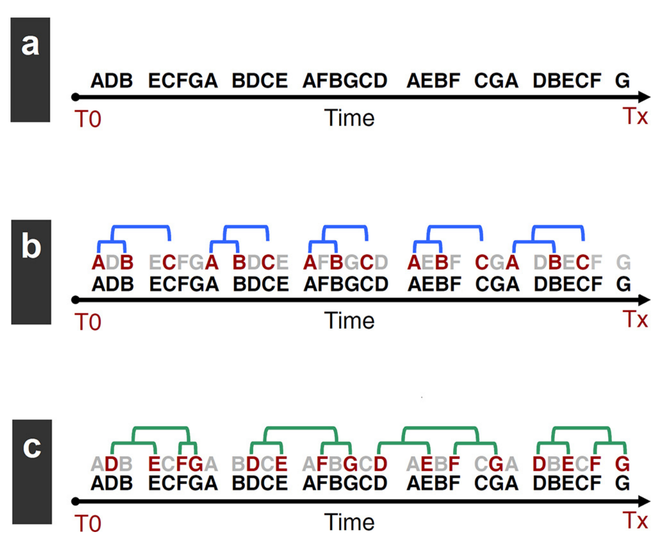

Fig. 1. String of hypothetical events (black letters) occurring during a given T0–TX time window. Two recurring sequences of events are present. If the extraneous events are removed the two sequences in (b) and (c) become evident.

a result, even the detection of a single sequence is hard if only the upper row of Fig. 1 is observed. Consistently, if the “background noise” is removed the two patterns become evident even at a very first glance (Fig. 1b and c). Notably, this is only a trivial example where events are represented by few alphabetical characters along an axis. Actually, the detection of recurring sequences is, by far, more complex in real observations where behavioral patterns flow in time and, as a consequence, the observer must necessarily deal with sequences that are not so easily perceptible (Eibl-Eibesfeldt, 1970). The crucial aspect is that, albeit a behavioral sequence is not immediately visible, it can still be essential in the “economy” and organization of behavioral architecture. Such an aspect calls for improved means of detection, data handling and analysis. By means of a multivariate technique known as T-pattern analysis (Magnusson, 2000), it is possible to identify recurring sequences of events that occur repeatedly and with statistically significant constraints on the interval length separating them, in human or animal behavior.

The following sections will focus on some historical notes concerning the development of this multivariate approach, underlying theories, concepts and how the T-pattern detection process works. In the second part of the review we will discuss the application of T-pattern analysis to the study of the temporal characteristics of behavior in different animal species, from rodents to humans.

2. Theoretical and historical background of T-patterns

The diverse theoretical and methodological background of T-pattern is mostly ethological, psychological and linguistic, but also in multivariate statistics and artificial intelligence (AI). After exploring existing methods and software and running into their limitations regarding the analysis of naturally occurring behavior as complex real-time processes, Magnusson set out to develop new structural concepts and tools and in particular for the discovery of its hidden patterns (Magnusson, 1978). Of direct importance is the work of the ethologists Tinbergen (1963), Montagner (1978) and Burton-Jones (1972) and the psychologists Duncan and Fiske (1977) all assigning much importance to observing and analyzing behavior in natural or relatively unconstrained conditions and focusing on the discovery of repeated behavioral interaction patterns. Chomskian linguistics (1957) brought attention to creativity and syntactic structure, while influence from Skinner’s radical behaviorism (1969) accounts for the strong focus on probability and real-time. In the early 70s, the complexity of empirical interaction analyses, such as those of Montagner (1978) and Duncan and Fiske (1977) clearly suggested that more automation was needed, but while computers were becoming more easily available, both computer literacy and software availability were limited.

After exploring available computational and statistical methods, it was in direct response to this situation, that the T-pattern concept with the first detection algorithms implemented as the *Theme software*, were created at the University of Copenhagen in the late 1970s and early 1980s and were first presented by their creator at an AI workshop at the University of Uppsala, Sweden, in a paper entitled “Temporal Configuration Analysis” (Magnusson, 1981). Magnusson has since added derived concepts and implemented them in *Theme* corresponding algorithms such as t-markers, t-associates, t-packets, t-template, and others, (Magnusson, 2000, 2004–2006), which together now form the T-system for behavior analysis and description. The first *Theme* version was about 3000 lines (in FORTRAN IV on PDP 8 computers) or one percent of its current size, now as a PC program available in both free and commercial versions (see http://www.patternvision.com).

The T-pattern represents the detection of some of the repetitive aspects of behavior, with a special focus on interactions. At this time it seems most easily explained by referring to a well-known aspect of everyday behavior, the repetition of various routines which often have names such as dinner, coffee-break, greeting, etc. Some are verbal like single words or standard phrases, verbal greetings, poems, laws, etc. Some are nonverbal, like waving, nodding, pointing, etc. while others constitute a mixture of both. All are combinations of simpler behaviors performed in a typical order with constraints on the time distances between them. This can be noted as:

$$X_1 \approx dt_1\, X_2 \approx dt_2\, X_3 \ldots X_i \approx dt_i X_{i+1} \cdots X_{m-1} \approx dt_{m-1} X_m \quad \text{(I)}$$

where, within occurrences of a pattern, its component X_i is followed approximately dt_i (≥ 0) time units later by its next component X_{i+1}. In terms of the intervals of variation of each *dt* term over a number of pattern occurrences, this can be noted as

$$X_1[d_1, d_2]_1\, X_2[d_1, d_2]_2\, X_3 \ldots X_i[d_1, d_2]_i X_{i+1} \ldots X_{m-1}[d_1, d_2]_{m-1} X_m \quad \text{(II)}$$

These intervals are the essential targets of the so called ‘critical interval detection algorithm’, which is at the heart of T-pattern detection (see below).

Moreover, an aspect contributing greatly to the power of the T-pattern model and T-pattern analysis is that the composition of T-patterns can be hierarchical and recursive, a pattern of patterns of patterns etc., and with each of the same structural kind down to some simplest elements. So, in (I) above, where any of the X terms may be patterns of the same structural kind, this describes a T-pattern.

A binary tree structure can be imposed in various ways on a sequence. For example, (A B C D E) can be represented as ((A B) (C D) E)) or as ((A (B C)) (D E)), etc. and some trees may reflect the inherent hierarchical structure better than others, thus being significant at every node and defining a detected T-pattern. T-patterns that are identical disregarding the tree (the parentheses) are considered equivalent.

The detection algorithm works in the opposite direction by searching for the simplest patterns first and gradually building the more complex ones from these, level-by-level. To do this, a method is needed to detect pairs of behaviors that constitute T-patterns. This means finding behaviors A and B, which more often than chance expectation, occur with approximately the same distance between them. That is, beginning at a particular distance ($d_1 \geq 0$) after occurrences of A, there is a time window [d_1, d_2] within which, more often than expected by chance, there is at least one occurrence of B. So, with A occurring at t the critical interval is [$t + d_1$, $t + d_2$] and it is the task of a special algorithm to search for such cases (Magnusson, 2000). The essentials of this algorithm are illustrated in Fig. 2. First, the distances, D, from each of the occurrences of A to the first following occurrence of B are measured leading to an A → B frequency distribution of such distances as shown in Fig. 2. Next, the algorithm searches for one of two types of critical intervals, called fast and free, respectively. The fast type [$d_1 = 0$, d_2], has d_1 fixed at zero (the time of A), while d_2 is adapted to the data. The free type allows the critical interval to start at any distance, ≥0, from A. In both the fast and the free case, the algorithm begins by testing the smallest interval that involves the greatest number of A’s, that is, the largest subset of D, it then gradually narrows and tests smaller intervals until either significance is reached (i.e. a critical interval [d_1, d_2] has been found) or no more narrowing is possible. In the fast case, where $d_1 = 0$, d_2 is thus first set to the longest A → B distance, max(D), and then to the next shorter, etc. until significance is reached or the search fails. In the free case, the most exhaustive current algorithm used in the *Theme* software is quite similar except that it starts with d_1 = min(D) and d_2 = max(D). Then, if there is no significance, d_2 is gradually decreased down to

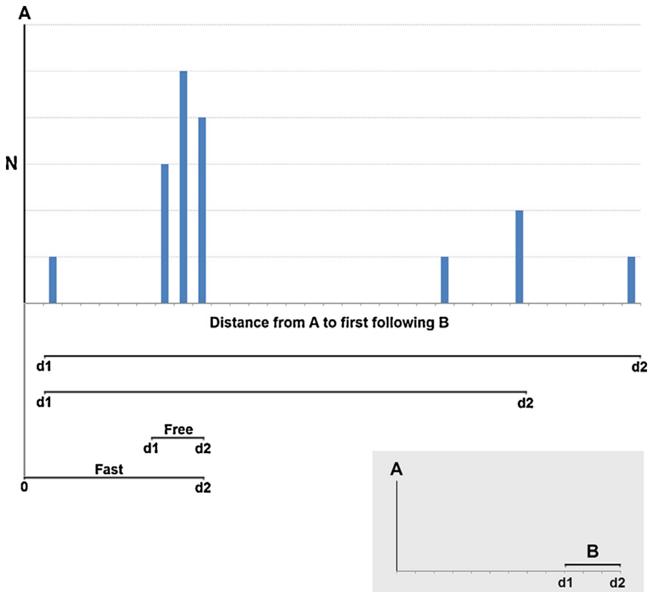

Fig. 2. Frequency chart for distances measured from every occurrence of A to the first following occurrence of B. Of the first three line segments below the chart marked d_1 to d_2, the first and second are the first tested by the free critical interval algorithm. The third marked free, indicates the interval where significance is then reached defining a critical interval. Finally, the last line segment marked fast, indicates where a fast critical interval $[0,d_2]$ might also be found in this data. The inset diagram shows a free critical interval positioned after each occurrence of A with more of its occurrences containing at least one occurrence of B than expected by chance.

d_1 as in the fast case, but if this does not reach significance, d_1 is increased to the next longer A → B distance in D and d_2 again to max(D) decreasing it as before until significance is reached or d_2 becomes smaller than d_1. The search fails when significance is not reached and d_1 cannot be further increased.

As the pattern-building evolution algorithm, driven by critical interval detections, constructs ever more complex patterns from the initial behaviors, it will compare all new patterns with those already detected dropping patterns that are either equivalent to already detected ones or are simply parts of larger ones and never occur independently (Magnusson, 2000).

Global statistical validation of detection uses a Monte Carlo approach through repeatedly randomizing the data and searching with the same parameters, obtaining the average and number of standard deviations for patterns of each length compared to those found in the original data. The *Theme* program provides two different types of randomization. One is the shuffling of each occurrence series, the other, more conservative, only shifts each series by a different random amount, thus keeping each one almost intact whilst randomizing the relations between all the series. Such statistical validation for each particular pattern is now also available considering only its series (its terminal event-types). Other types of randomizations than these two already build into the Theme program may be considered by the generation and analysis of data randomized in different ways.

Note that critical interval relationships between T-pattern components are essentially correlational, but often suggest causality as, for example, when consecutive parts of the same pattern are performed by different actors (agents, subjects, individuals, groups, etc.). As the input data, a T-pattern may involve any number of subjects performing any number of different behaviors at the same time points, so no order needs to be artificially imposed.

In essence, multi-stage T-pattern detection algorithm can be seen as a combination of a sequential clustering algorithm (see Dawkins, 1976), adding focal consideration of real-time and intensive significance testing based on binomial probability theory and what today is referred to as an evolution algorithm.

The input to the algorithm is simply a set of (time) point series each representing the beginning or end time points of some type of behavior performed by an actor, agent, etc. called event-type or a T-event type, for example, "s6,b,run" (s6 begins to run), as well as the observation interval(s) within which they occurred. The data is thus simply two columns: the time stamp and the event-type. Any time unit may be used and time is always in the smallest time unit defining the temporal resolution, and thus always as an integer. The model is therefore scale independent. Resolutions from approximately a few millionths of a second to a day have been used for the study of, respectively, neuronal interactions and human hormone related behavior.

As can be seen, each T-pattern has many aspects or parameters, such as its length (m) and the depth (number of levels) of its detection tree as well as the actual times of occurrence of each component within each occurrence of the pattern, as well as the distances ≈dt between them. The number of actors involved and how often they alternate within each pattern is also provided for all patterns by the *Theme* software. Statistics of such measures for all patterns detected within a dataset allows comparisons of groups of such datasets, typically reflecting an experimental design and sometimes revealing effects hidden to standard methods, based directly on frequencies of coded behaviors.

Fig. 3d shows T-patterns detected in the tiny illustrative real-time behavior record in Fig. 3a consisting of the occurrence series of event-types A, B, C, D, E and F (noted a, b, c, d, e & f). The search begins by considering each of the N * N (Left Right) series pairs (non-symmetrical, Left–Right not equal to Right–Left), measuring all distances from Left to the first following Right (for example, from each a to the first following b) and searching the resulting distribution for a critical interval relationship defining the occurrences of a T-pattern (Left Right), for example, (A B). First the simplest T-patterns are thus detected involving only raw data series, and then more complex patterns are detected as patterns of these and possibly some of the initial data series. In Fig. 3b, occurrences of A and B repeatedly occur with similar distances between them forming the occurrences of a T-pattern (A B), and in Fig. 3c the same is true for the occurrences of C and D thus defining the occurrences of T-pattern (C D). In Fig. 3d, relating these two detected T-patterns, it appears that an occurrence of (A B) is sometimes followed by an occurrence of (C D) after a significantly similar delay thus defining the occurrences of the more complex T-pattern ((A B) (C D)). Note that not all occurrences of either the initial series or T-patterns (A B) and (C D) are involved in the longest pattern ((A B) (C D)).

Realistic behavior records are typically far more complex involving tens or hundreds of series in the initial data, so detecting T-patterns simply by inspection or through the use of methods not designed specifically for the task is normally impossible.

3. Validity of the model

While the first results of applying T-pattern Analysis to children's interactions were positive, the adequacy or validity of the T-pattern model for other behaviors, situations and species still needed to be tested. Magnusson further clarified the T-pattern concept definitions, and improved algorithms and their implementations in *Theme* (Magnusson, 1988). In the early 90s, the T-pattern diagram has been created and implemented as an integral part of *Theme*. It shows, at-a-glance, all the point series and hierarchical connections between their points involved in a T-pattern (Magnusson, 1996, 2000). Further developments in T-pattern analysis resulted in two papers on children's dyadic problem solving (Beaudichon et al., 1991; Magnusson and Beaudichon, 1997) and a

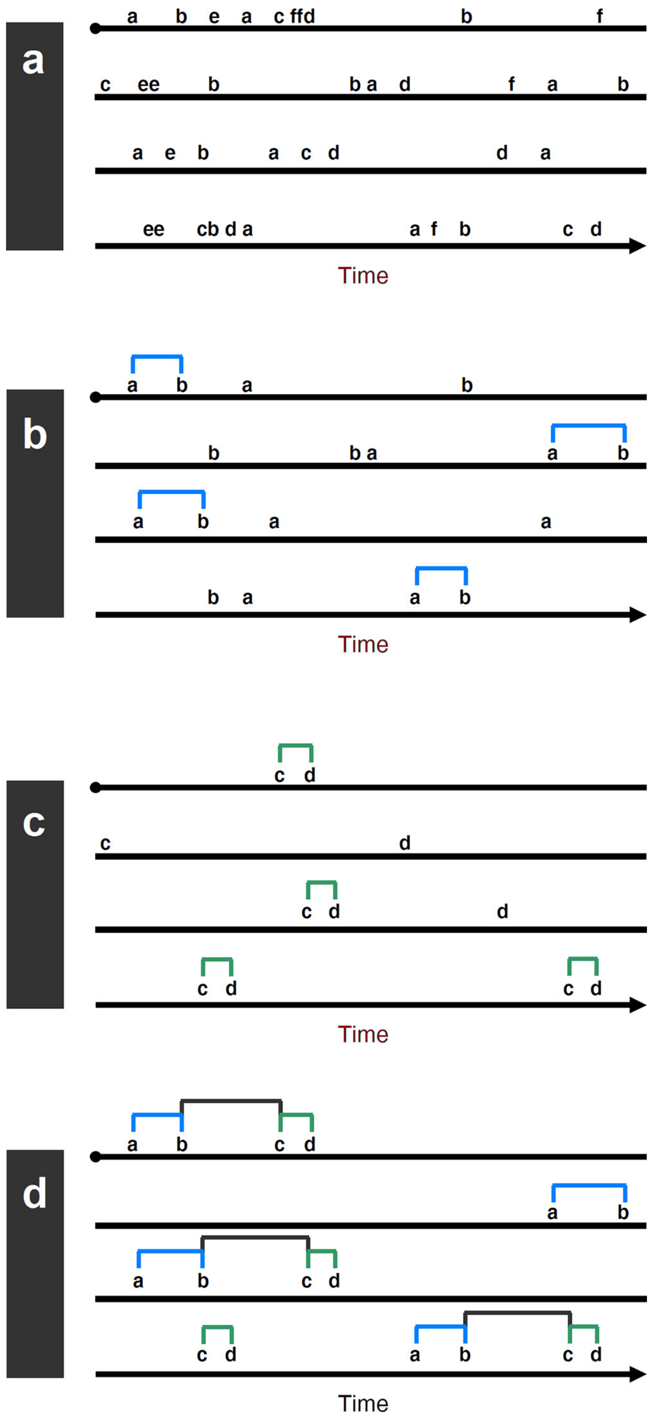

Fig. 3. Panel (a) shows a behavior record with the occurrences of event-types A, B, C, D, E, and F, noted as a, b, c, d, e and f. Panels (b) and (c) indicate how, respectively, T-patterns (A B) and (C D) are found within the illustrative minute behavior record of panel (a). Panel (d) shows T-patterns (A B), (C D) and ((A B) (C D)) detected within this data.

series of doctoral theses (Bensalah, 1992; Tardif, 1996a; Sigurdsson, 1997; Sevre-Rousseau, 1999; Schwab, 2000) with related publications all implicating T-pattern analysis (Tardif, 1996b; Tardif and Plumet, 2000; Plumet and Tardif, 2005). Magnusson, in another paper (Magnusson, 1989), illustrated that non-cyclical behaviors may form highly cyclical T-patterns and a doctoral thesis implicating T-pattern analysis of mouse behavior (Feron, 1992) has been produced. This research and development has always been carried out in the context of empirical behavior research in collaboration with researchers in different university laboratories in the USA and Europe (Anolli et al., 2005; Grammer et al., 1998; Filiatre, 1986; Montagner et al., 1990; Casagrande, 1995; Castañer et al., 2009, 2010a,b; Nicol et al., 2005, 2014; Casarrubea et al., 2009, 2010, 2011; Casarrubea et al., 2013a,b, 2014; Burgoon et al., 2014a,b; Sandman et al., 2012). However, beside specific results of each research, when a T-pattern is detected three pivotal questions do arise: *what a t-pattern is*, *why does it exist* and, last but not least, *what does it mean*. The first question, "*what a T-pattern is*", is more or less exhaustively addressed in the method sections of all the articles dealing with such a multivariate technique (see below). The answer, namely, a recurring sequence of events sharing statistically significant inter-relationships, is usually sufficient for the aim of the given study. For instance, if the research is on behavioral stereotypies, it is clear that the explanation of T-patterns in terms of a recurring sequence of behavioral acts will perfectly fit with the study and the presentation of the results.

The second question, "*why does a T-pattern exist*", is not usually discussed because the answer would require a debate almost certainly far from the objectives and arguments of the research, whatever it is. Actually the answer is intrinsically linked with the emerging nature of these phenomena. Indeed, it is essential to bear in mind that the very heart of a T-pattern lies in the fundamental concepts of "organization" and "self-organizing systems", that is, as underlined by the British psychiatrist and neuroscientist Ross Ashby, as soon as the relation between A and B becomes conditional on C, then a necessary component of organization is present and, as a consequence, the basic assumption that we are speaking of a whole composed of parts (Ashby, 1962). In this view, a given ((A B) C) T-pattern can be considered as a self-organization phenomenon emerging under particular constraining conditions (Magnusson, 2000).

Finally, as to the third question, namely "*what does a T-pattern mean*", the answer depends on the structure of the given T-pattern (that is the events in sequence) and, crucially, on the context. A simple example, in this sense, could be useful. Let's imagine a subject performing, in a given environment, a relatively simple behavior consisting of a sequence of four events: focusing → approaching → immobility → walking away; in other terms, the subject carefully observes something, walks toward the object of interest, remains immobile for a while and, finally, walks away in another direction. If the experiment simply consists of a freely moving person observed for a given time period, it might be possible to conclude that such pattern represents a normal sequence of environmental exploration carried out by the subject in a novel environment. A completely different explanation would be provided if an aversive cue, e.g., an unexpected or loud noise would be presented to the subject: the whole sequence might be indicative of fear-related behavior. Thus *the meaning* of a T-pattern strictly depends on *the context* where the pattern is performed, on *the problem* that the subject must face, and finally, on *the solution* performed to deal both with the context and with the problem as well. In this sense, the inspiring idea that "*each pattern is a three-part rule, which expresses a relation between a certain context, a problem, and a solution*" (Alexander, 1979), might represent the best answer for such a latter question. In a more general or abstract manner it may be noted that organization of matter and all sorts of known phenomena seem to be hierarchically and recursively organized over many orders of magnitude in a fractal manner, that is, as self-similar patterns of patterns, etc. (Baryshev and Teerikorpi, 2002).

Each instance (occurrence) of a T-pattern is an entity that has a beginning and an end in time and space just as behavioral categories such as running, sitting, pointing, laughing, standing, crawling, blinking, etc. and may thus be subjected to the same kinds of analyses and modeling of their distributions in time and space, for example, Markov Chain analysis (Grinstead and Snell, 2012), Iwao's omega (Iwao, 1977), and numerous other kinds of analyses. While Markov Chain models traditionally involve a minimum of contextual memory, T-pattern analysis is concerned with contextual effects in terms of multiordinal or complex-conditional probabilities between simple behaviors and patterns of these and is thus potentially useful in various molar approaches such as, for example, advocated by Rachlin (1986) and decision making processes as discussed by Rachlin and Siegel (1994), Kudadjie-Gyamfi and Rachlin (1996) among others. T-pattern analysis may thus find use within the growing multidisciplinary field of neuroeconomics (Glimcher, 2002; Egidi et al., 2008).

The two following sections will discuss applications of T-pattern analysis to the study of the temporal characteristics of behavior in different animal species, including human beings.

4. T-patterns in animal behavior

Early application of T-pattern analysis to the study of animal behavior can be found in various papers concerning feeding in fowls. On this subject, Martaresche and colleagues (2000) demonstrated that T-pattern analysis can be successfully applied to study feed pecking in these animals. The authors showed that pecking at feed is composed of two distinct sets of acts: events organized in T-patterns little affected by the form of the pecked particles and events not structured in T-patterns that might be involved in sensory information. In a following study, Merlet et al. (2005) analyzed the behavior of two different genotypes of broiler breeder. The authors compared three different feeding protocols: animals fed "ad libitum", animals under an intermediate feed restriction and, finally, animals with a constant feed restriction. Results showed that the two genotypes exhibited behavioral strategies that were quite different but adapted similarly to the different feed allowances. Hocking et al. (2007), applied three different analytical approaches: conventional quantitative assessments of behavior (frequencies, durations, etc.), de-trended fluctuation analysis and T-pattern analysis, to study broiler breeders with diets at two levels of feed restriction. Concerning quantitative analyses, results showed that more time was spent drinking before feeding, when compared with the afternoon; whilst multivariate T-pattern analysis results showed that bouts of longer mean duration and longer total duration were detected before feeding, when compared with the afternoon. Interestingly, the authors conclude that a technique to assess the structure of behavior such as T-pattern analysis, in addition to conventional analyses, should be used in behavioral research to obtain a more complete representation of the behavioral organization. Altogether, these studies concerning feeding behavior in fowl are potentially very useful in that, uncovering more information concerning the feeding behavior of these animals, might contribute to an improvement of their well-being within the breeding farms. In particular, the work of Hocking and colleagues (2007) is also interesting since the authors utilize conventional analyses, such as the assessment of latencies and durations, together with multivariate ones. Hocking and colleagues recognized that descriptive/quantitative approaches are useful because they provide information concerning each investigated behavioral element. On the other hand, such approaches are not able to detect the most important features of behavior, being the functional relationships among behavioral elements. Therefore, descriptive approaches to the analysis of behavior should, where and if possible, be partnered with different suitable techniques of behavioral investigation such as multivariate T-pattern analysis. Another interesting application of T-pattern analysis in the study of birds' behavior has been carried out by Brilot et al. (2009). These authors used both T-pattern analysis and Markovian analysis to identify temporal sequences in the locations that a starling occupied within its cage. Results showed that T-pattern analysis was able to quantify individual differences in the animals' use of space and that the detected T-patterns were predictors of abnormal behavior. The authors concluded that multivariate T-pattern analysis has the important advantage to detect patterns in sequences of behavior that would be invisible to Markov chain analysis. In two more recent studies, the same research group has applied various analytical approaches, including T-pattern analysis, to analyze cognitive performance and to compare the development of stereotypic route-tracing in hand-reared and wild-caught starlings (Feenders and Bateson, 2012, 2013). The number of different T-patterns and the total number of T-patterns detected have been used as measures of route-tracing behavior. Results demonstrated that wild-caught starlings showed higher numbers of T-patterns indicating more route-tracing (Feenders and Bateson, 2012). Interestingly, some evidence showed that hand-reared starlings were noticeably less neophobic and less impulsive than wild-caught ones (Feenders and Bateson, 2013).

A number of research projects, using T-pattern analysis, investigated insects' behavior. Hemerik and colleagues (2006) proposed the use of different analytical approaches to study the parasitoid foraging behavior. The authors used a maximum likelihood method to detect sudden changes (i.e., breakpoints) in their event log files. Moreover, to demonstrate modifications of insects' activity, they utilized different statistical tests within and between matrices followed by a T-pattern analysis. This article highlights the feasibility and the usefulness of integrating different multivariate approaches in the evaluation of behavioral dynamics otherwise undetectable. Two additional studies have successfully employed T-pattern analysis to investigate insects' activity. Arthur and Magnusson, 2005 proposed an analysis of Drosophila courtship behavior. The results showed several behavioral patterns usually undetectable at a normal temporal resolution. Interestingly, the authors showed that high frequency of specific insect's activities did not imply the inclusion of these frequent behavioral events in temporal patterns. In a more recent article T-pattern analysis has been used to study the behavior and maternal territoriality of insects of the order Embioptera (Dejan et al., 2013). The analysis revealed various interactions occurring between residents and intruders and that the behavioral responses of intruders to female signals were not predictable.

Beyond birds and insects, a consistent slice of behavioral studies using T-pattern analysis has concerned rodents. Bonasera and colleagues (2008) have applied T-pattern analysis as a novel method for the quantification of psychostimulant-evoked route-tracing stereotypy in mice. Following the administration of various drugs, such as amphetamine, the authors found a clear-cut modification of number and length of detected T-patterns. It was concluded that, by means of T-pattern analysis, a versatile pattern detection and quantification can be achieved. Also, they underlined that one of the most important advantages of this multivariate technique lies in its ability to detect recurring patterns without any prior assumption on specific pattern features. This aspect has also been discussed in an article from Casarrubea et al. (2009). Here, the authors utilized quantitative evaluations of behavior (e.g., percent distributions, frequencies) and various multivariate approaches, including T-pattern analysis, to describe rat behavior in the open-field. Casarrubea and co-workers underlined that all the approaches based on transition matrices represent the comprehensive observational period like a snapshot, where all the patternings among the behavioral elements are represented together in a big portrait lacking of temporal dimension. On the other hand, by means of T-pattern analysis, the information concerning time is added and behavioral events, possibly uncommon, may be found to have a crucial role in the temporal architecture (Casarrubea et al., 2009). During the following years, these authors applied T-pattern analysis to study anxiety and anxiety-related behavior in rats tested in the hole-board and elevated plus maze (EPM). Results showed that the behavior of the rats, in the hole-board (Casarrubea et al., 2010) and in the EPM (Casarrubea et al., 2013a), is organized on the basis of events which occur sequentially and with statistically significant constraints on the interval length separating them. Importantly, the administration of anxiety modulators, such as diazepam, has been found to significantly modify the comprehensive temporal organization of the behavior in the hole board apparatus (Casarrubea et al., 2011). Concerning the EPM, the behavior of the Wistar rat has been compared with the behavior of a more anxious strain, the Dark Agouti (Casarrubea et al., 2013b); results demonstrated significant divergences in the temporal architecture of the behavior of the two strains of rat. Overall, these researches demonstrate that T-pattern analysis is a robust and reliable tool to study the emotional profile of rodents in various experimental assays. Also, an interesting aspect emerging from the articles of Casarrubea and colleagues concerns the approach to illustrate T-patterns and their real-time occurrences. Indeed, in the classical output of T-pattern analysis, events within each sequence are linked by means of dendrogram-like tree structures. Such a representation has the benefit to show both the structure of the T-patterns and their real-time distribution. Nonetheless, when the number of detected patterns is high the representation of T-patterns by means of tree structures, as illustrated in Fig. 1b and c, could be impossible owing to the enormous amount of space required. For these reasons the authors have developed the representation of T-patterns by means of behavioral stripes, that is, the illustration of the onset of each T-pattern, along the *x*-axis, by means of vertical marks (Casarrubea et al., 2010, 2011, 2013a,b, 2014). The authors also suggest that, to provide information concerning the structure of the patterns, each stripe should be partnered with a table reporting all the terminal strings of the patterns represented in stripes. Another interesting application of T-pattern analysis in rodents has been recently proposed by a group from the Rudolf Magnus Institute to study quinpirole-induced compulsive-like behavior (de Haas et al., 2011, 2012). Results showed that, following drug administration, the animal performed a smaller behavioral repertoire and that, similarly to patients with obsessive–compulsive disorder, quinpirole-treated animals performed these behaviors with a high rate of repetition.

T-pattern analysis has been also applied to detect and study sequences of neuronal activity. Nicol and colleagues (2005, 2014), using a multielectrode array, have recorded the activity of neurons of the olfactory bulb in rats. The results of this study clearly demonstrated that in the olfactory bulb of the anesthetized rodent the sequences of discharge are strictly related to the respiratory activity and odor information processing (Nicol et al., 2005, 2014). Interestingly, these evidences underline that T-pattern analysis can be successfully used not only to study animals' and humans' behavior but also to evaluate neuron activity.

In two recent articles from Horn et al. (2011, 2013), T-pattern analysis has been applied to study emetic behavior in the Suncus Murinus, a little mammal, similar to a rodent, belonging to the family of Soricidae. It resulted that several non-random patterns of behavior are associated with emesis, including sniffing, changes in body contraction and locomotion (Horn et al., 2011). In addition, the use of new dynamic behavioral measures to more comprehensively evaluate emesis and the impact of therapies have been proposed (Horn et al., 2013).

A group from the Russian Academy of Sciences applied T-pattern analysis to study the behavior of a group of wolves freely moving in a 1.5 ha forest (Yachmennikova and Poyarkov, 2011). On the basis of a complex ethogram encompassing both individual and social activities, the authors detected a high number of T-patterns in the behavior of the observed animals. The authors suggested that the evaluation and description of the structure of time patterns, in which the activities of each subject are interrelated, offers a new way of behavior description of the wolves.

T-pattern analysis has been utilized by Jonsson and colleagues (2010) to study vertical and horizontal movement patterns in the Atlantic cod, one of the most important fishes from a commercial/economic point of view. The authors found a high number of temporal patterns of repeated vertical movements, speed and acceleration. In addition several patterns were also detected within and across individual cod vertical movements. Table 1 summarizes various applications of T-pattern analysis, with their respective references, in the study of human and animal behavior.

5. T-patterns in human behavior

During the past few decades *Theme* has been applied in a number of different fields studying various dimensions of human behavior and interaction. Numerous studies using the T-pattern detection algorithm have demonstrated that the organization or structure of behavior, both verbal and non-verbal, is influenced by variables such as hormonal levels, personality, situation and culture.

Over the years, a number of studies on autism spectrum disorders have been published. Tardif et al. (1995) conducted a micro-analysis of social interactions between autistic children and normal adults in semi-structured play situations using *Theme*. The study was designed to identify the qualitative and temporal characteristics of the exchange structures of autistic children interacting with an adult and to analyze and compare the implementation of their interactive behavior in a range of play situations. The results showed that in this structured situation the autistic children engaged in a variety of behaviors for communicating with the adult, and that 8 of the 10 children repeatedly exhibited structures of interaction. These patterns were found to depend on the intelligence quotient (IQ, a score designed to quantify human intelligence based on several tests) of the child, but involved a certain number of peculiar characteristics (parasitic behaviors, lack of initiative, maladapted visual behavior, etc.), even for the children with the highest IQ scores. Warreyn et al. (2007) investigated initiating and following declarative joint attention and initiating requesting joint attention in a group of preschool children with autism spectrum disorder (ASD) and an age-matched control group. Different forms of joint attention were elicited while children interacted with their mothers. Temporal coordination of the children's joint attention behavior was examined using three levels of coding. Children with ASD showed fewer, but similar, requesting abilities and slower point following combined with an abnormal behavioral pattern of looking at the other person's pointing finger instead of the object pointed at. Initiating declarative behavior was qualitatively and quantitatively different, characterized by isolated instances of communication instead of a fluent shift of attention between object and person.

Masunami et al. (2009) studied, utilizing the Iowa gambling task, decision making strategies in children with attention-deficit hyperactivity disorder (ADSD). The authors analyzed T-patterns with rewards, with punishments, and without rewards and punishments during the task. Results demonstrated that children with ADSD had fewer temporal patterns with punishments and exhibited a significant tendency to have many patterns with rewards. The authors concluded that children with this disorder would be impaired in decision-making strategies on the basis of their abnormal sensitivity to punishments and rewards.

Lyon et al. (1994) studied the importance of temporal structure in analyzing schizophrenic behavior comparing outpatient schizophrenics to normal control subjects. Their results revealed

Table 1
Synoptic table presenting the applications of T-pattern analysis, with their respective references, in animal and human behavior, as discussed in Sections 4 and 5.

Subjects	Research topic	References
Animal		
Starlings	Stereotypic behavior	Feenders and Bateson (2012) and Brilot et al. (2009)
Starlings	Cognitive performance	Feenders and Bateson (2013)
Fowls	Feeding behavior	Martaresche et al. (2000), Merlet et al. (2005) and Hocking et al. (2007)
Parasitoids	Foraging behavior	Hemerik et al. (2006)
Drosophila	Courtship behavior	Arthur and Magnusson (2005)
Embioptera	Maternal territoriality	Dejan et al. (2013)
Mice	Route-tracing stereotypy	Bonasera et al. (2008)
Mice	Compulsive-like behavior	de Haas et al. (2011, 2012)
Rats	Anxiety related behavior	Casarrubea et al. (2010, 2011, 2013a,b, 2014)
Rats	Neuronal firing	Nicol et al. (2005, 2014)
Shrews	Patterns associated with emesis	Horn et al. (2011, 2013)
Cods	Patterns of swimming	Jonsson et al. (2010)
Wolves	Social behavior	Yachmennikova and Poyarkov (2011)
Human		
–	Autism	Tardif et al. (1995) and Warreyn et al. (2007)
–	Schizophrenia	Lyon et al. (1994) and Lyon and Kemp (2004)
–	Self-injurious behavior	Kemp et al. (2008) and Sandman et al. (2012)
–	Attention-deficit hyperactivity disorder	Masunami et al. (2009)
–	Social interaction in infants or children	Montagner et al. (1990) and Magnusson (2000)
–	Pervasive developmental disorder	Willemsen-Swinkels et al. (2000)
–	Behavioral symptoms of dementia	Woods et al. (2014)
–	Self-directed speech and non verbal behavior	Kuvalja et al. (2013)
–	Language and behavior patterns	Blanchet et al. (2005)
–	Repeated suicide risk assessment	Haynal-Reymond et al. (2005)
–	Gender relation and courtship	Grammer et al. (1998) and Sakaguchi et al. (2005)
–	Communicative feedback	Allwood et al. (2007)
–	Patterns in behavior and hormone levels	Hirschenhauser et al. (2002) and Hirschenhauser and Frigerio (2005)
–	Self-esteem and social interaction	Jonsson (2006)
–	Communication and conversation patterns	Agliati et al. (2005, 2006b), Koch et al. (2005) and Koch (2007)
–	Stress factors and routine tasks	Brdiczka et al. (2009, 2010) and Su et al. (2013)
–	Team effectiveness and team interaction	Stachowski et al. (2009) and Zijlstra (2012)
–	Sport/physical activity (soccer)	Borrie et al. (2002), Anguera-Argilaga and Jonsson (2003), Anguera-Argilaga et al. (2003), Bloomfield et al. (2005), Jonsson et al. (2003, 2004, 2006), Camerino et al. (2012) and Lapresa et al. (2013a,b)
–	Sport/physical activity (motor skills and dance)	Castañer et al. (2009, 2010a,b) and Torrents et al. (2010)
–	Sport/physical activity (basketball)	Fernandez et al. (2009)
–	Sport/physical activity (swimming)	Louro et al. (2010)
–	Sport/physical activity (martial arts)	Gutierrez et al. (2009, 2011)
–	Interactions human–dog	Kerepesi et al. (2005)
–	Interactions human–cat	Wedl et al. (2011)
–	Interactions human–artificial agent	Kerepesi et al. (2006), Jonsson and Thorisson (2010) and Agliati et al. (2006a)

that response of schizophrenic outpatients, in comparison to control subjects, had a larger number of significant temporal patterns, an increase in different types of patterns and more branching (connectivity) of patterns at a higher level. The latter indicates a higher degree of internal structure. These results were not predicted by standard diagnostic procedures, but are in agreement with studies of two-choice behavior in schizophrenia based on the Lyon-Robbins theory of behavioral change, which has possible relationship to dopamine/acetylcholine imbalance in the brain. Diagnostic procedures in schizophrenia might benefit from tests oriented toward these findings, which are also consistent with Bleuler's original descriptions of schizophrenic symptomatology. Lyon and Kemp (2004) used *Theme* as an objective method for assessing cognitive disturbances in schizophrenia. Their objectives were to compare responses of schizophrenic patients with those having mood, schizoaffective, or severe anxiety disorders, and with healthy control subjects. The results showed that schizophrenic and manic patients showed excessive numbers of, and more complex T-patterns than controls. Schizophrenic and manic patients frequently demonstrated repetitive (stereotyped) responses, an effect never seen in healthy controls. Although clozapine reduced both excessive T-pattern structure and stereotyped responding, it also reduced growth of responding to the coin reinforcements. The authors concluded that significant T-pattern increases may represent a common, time-related symptom of schizophrenia and mania. Clozapine's effect on T-pattern production suggests that receptor effects, other than the DA D2 antagonism of typical neuroleptics, may be relevant to these findings.

Examining how temporal patterns of self-injurious behavior (SIB) correlate with stress hormone levels in the developmentally disabled, Kemp et al. (2008) investigated whether recurrent temporal patterns of SIB were related to morning levels of two Proopiomelanocortin-derived hormones: beta-endorphin (betaE) and adrenocorticotropic hormone (ACTH). *Theme* was used to quantify highly significant (non-random) T-patterns. Pearson's product-moment analyses revealed highly significant correlations between the percentage of T-patterns containing SIB and basal levels of both betaE and ACTH, which were not found with any other "control" T-patterns. These findings support the hypothesis that the recurrent temporal patterning of SIB represents a unique behavioral phenotype directly related to perturbed levels of Proopiomelanocortin-derived stress hormones in certain individuals with severe developmental disabilities. Sandman et al. (2012) studied the role of self-injury in the organization of behavior using *Theme*. The results indicated that acts of self-injury contributed to both more patterns and more complex patterns. Moreover, self-injury left its imprint on the organization of behavior even when counts of self-injury were expelled from the continuous record. The authors concluded that behavior of participants was organized in a more diverse array of patterns when self-injurious behavior was present and that self-injuring acts may function as singular points, increasing coherence within self-organizing patterns of behavior.

In the field of developmental psychology there is a long tradition of studying temporal aspects of behavior and interaction. One of the earliest from Montagner et al. (1990) reported on *Theme* as a new method developed for the study of the genesis and regulations of the behavior of infants in interactive situations. The results revealed that 4-month-old infants showed high level competence in visual attention spans, a varied and complex behavior and interaction (INT) processes, and special relationships between infant-infant INTs and infant–mother INTs. Periodic behavioral outbursts were observed, along with the existence of significant intra- and inter-individual behavioral patterns, which facilitate the mutual adjustment processes between both infants. Willemsen-Swinkels et al. (2000) studied children with a pervasive developmental disorder (PDD), children with developmental language disorder, and normally developing children seeking to answer questions concerning attachment and autistic behavior. Children with both a PDD and mental retardation were more often classified as disorganized (D). The authors concluded that the low number of long dyadic patterns detected in children with a D-classification may be indicative of an overall pattern of disorganized social behavior. They speculated that the number of patterns found in children with a D-classification is below this optimal number of patterns, but recognize that more research is needed on the important aspects of sequence and timing of behavioral elements.

Woods and colleagues (2014) recently presented an article aimed at the characterization of complex behavioral symptoms of dementia in two groups of patients. Results indicate clear differences between the two groups from late afternoon to early evening. The groups differed significantly in age, comorbidities, antianxiety medication, and the number and complexity of patterns of vocalization and restlessness. The authors showed that T-pattern analysis has been able to identify behavioral patterns that drove the overall time of day pattern.

Kuvalja et al. (2013) examined patterns of co-occurring nonverbal behavior and self-directed speech and compared three methodological approaches to their data. Self-directed speech was proposed to have a mediating role in the emerging self-regulatory behavior of young children. Studies with correlational findings have lent support to this hypothesis but fail to delineate the real-time temporal interactions between self-directed speech and self-regulatory behavior. The results obtained from T-pattern analysis revealed qualitative differences between these two groups of children, in their use of self-directed speech, which were not detected by the other two methods.

One of the earliest *Theme* publications on behavioral patterning in dyadic interaction and therapeutic interviews comes from Blanchet and Magnusson (1988), studying the effect of an interviewer's reiteration in referential and modal modalities on the modalization rate in a subject's discourse. Blanchet et al. (2005) continued along similar lines, studying language and behavior patterns in therapeutic interactions. The goal of their study was to describe an interaction session between a therapist and a patient. Two types of analysis were conducted: a hierarchical semantic analysis and an analysis of temporal behavior patterns using *Theme*. The results showed that therapeutic interventions first result in a deconstruction of the patient's initial point of view, followed by reinforcement of the patient's new point of view by means of confirmation. In this phase of reconstruction, the patient is led to reinterpret his symptoms along the lines encouraged by the therapist. The analysis of temporal patterns showed that the deconstruction phase involved many non-verbal signs associated with challenges to the patients' statements, and that certain themes in the patients discourse were regularly associated, throughout the session, with gestures and hand movements that might constitute the gestural signature of these themes.

Theme has also been applied in a study of non-verbal communication in doctor–suicidal patient interview. In a study conducted by Haynal-Reymond et al. (2005) focus was on current techniques of repeated suicide risk assessment, which have not proven to be reliably predictive. Since the judgment of clinicians relies partly on nonverbal signs, such as facial expressions, the authors assumed that if differences in patients and/or interviewer's facial expressions appeared between subjects who were to make subsequent attempts (Repeaters) and those who were not (Non-Repeaters), this could lay the foundations for new ways of prediction. Patients admitted after a suicide attempt were video-recorded during an interview with a psychiatrist. After the interview, the therapist was asked to assess the suicide risk. At 24-months follow-up, the authors identified Repeaters, who were then matched with the Non-Repeaters. To code the doctor's and patient's facial behavior, they used Ekman and Friesen's "Facial Action Coding System" (FACS) and then analyzed the behavioral differences with both groups. Results indicated an average activation of all coded units, peri-ocular activation, and duration of her gaze straight at the patient, which were all significantly higher, distinguishing correctly 81.8–90.9% of the patients. By contrast, the doctor's written predictions were erroneous: only 22.7% of the patients were correctly classified. This fact reflected the doctor's perception of risk, without awareness. Different types of behavioral patterns were found to occur exclusively by either repeaters or non-repeaters and significant differences were found in the complexity of patterns between groups.

Gender relation and courtship has also been the subject of *Theme* analysis in several research projects. Grammer et al. (1998) published a paper on the courtship dance, analyzing the non-verbal synchronization in opposite-sex encounters. The study examined the existence of behavioral correlates of synchronization on different levels of analysis and methods. Authors were unable to demonstrate a relation between synchronization defined in terms of movement echo or position mirroring and subjective experience of pleasure and interest in opposite-sex encounters but significant results were found when looking at the temporal patterning of behavior. If a female was interested in a male, highly complex patterns of behavior with a constant time structure emerged. The patterns were pair-specific and independent from behavioral content. To follow up the Grammer paper, Sakaguchi et al. (2005) conducted a study on initial interpersonal attraction between mixed-sex dyad and movement synchrony. In a waiting room situation, initial interaction of unacquainted mixed-sex dyads were filmed, and authors investigated whether movement synchrony between a dyad related with the formation of interpersonal attraction. Movement synchrony measures calculated related to a participant's interest in the partner more strongly in the first minute than in the last minute. However, the relationships were mostly explained by the increase of movement frequency. The movement synchrony measure that remained to be a significant signal was the repetitiveness of behavior time-sequences. A dyad with a male participant interested in the partner decreased the repetitiveness of movement synchrony in the first minute. On the other hand, a dyad with a female participant who reported frequent sexual approaches by male strangers showed an increase in the repetitiveness of movement synchrony. This suggested that such behavioral characteristics of frequently approached women tend to be interpreted as a courtship-like signal by male strangers. Only among dyads with frequently picked up women, the increase of female self-synchrony patterns positively correlated with male interest in them, circumstantially supporting the explanation. T-pattern analysis has been applied, by Allwood et al. (2007), to study communicative feedback, that is, the given set of vocal and/or bodily expressions underlying a correct and effective communication between two subjects. Results demonstrated the existence of highly complex feedback patterns in terms of hierarchical organization.

Hirschenhauser et al. (2002) and Hirschenhauser and Frigerio (2005) published two papers where *Theme* was used to study patterns in behavior and hormone levels. Monthly patterns of testosterone and behavior in prospective fathers were analyzed. The results indicated a varying number of complex nonrandom interaction patterns of testosterone with sexual activity, but also with weekly (i.e., Saturdays) and monthly intervals (i.e., 28-day full-moon intervals). The social context of the occurrence of specific pattern combinations was elaborated using parameters from the men's self-reported general life history profiles. Peak hormone levels occurred around weekends in the majority of the males. The 28-day monthly interval coincided with testosterone peaks only in those of the paired men who reported a current wish for children ("prospective fathers"), but not in unpaired men or in those who did not wish to have children with their current partner. Rather than representing a direct regular pattern of the male testosterone per se, the observed patterns suggest that men have the facultative potential to adjust their testosterone responses to their female partner's cycle. In line with the interactions between behavior and androgens observed in vertebrates in general, this study adds an example of the mutual character of hormone-behavior interactions and, thus, for the social context of testosterone patterns in human males.

Theme has also been applied in research on the relation between personality dimensions, language development, emotion and culture. Jonsson (2006) examined the relation between personality dimensions, self-esteem and social interaction. Earlier studies (Jonsson, 1996, 1997, 2000) had suggested a strong relationship between the level of subjects' self-esteem and the number of real-time behavioral patterns produced in dyadic interaction situations. Significant differences had also been found in real-time behavioral patterns produced in dyadic interactions between subjects who considered themselves to be friends, versus those who were strangers. It was though unknown whether such behavioral analysis would reveal a difference in real-time patterns produced by persons with different scores on the Eysenck personality questionnaire. These ideas were tested analyzing 24 dyadic interactions between male students. Results indicated that these interactions are highly synchronized and structured. A strong correlation was found between subjects' self-esteem and the complexity and frequency of behavioral patterns detected. A positive correlation was also found between subjects; personality and complexity and frequency of patterns. Certain pattern types were found exclusively to be produced by extraverts and others by introverts. High and low self-esteem subjects were also found to produce different types of behavioral patterns.

Focusing on non-verbal behavior and cultural differences, Agliati et al. (2005, 2006b) analyzed conversation patterns in Icelandic and Italian people, looking for similarities and differences in rhythm and accommodation. Data highlighted the country effect on conversation rhythm: number and frequency of time patterns were deeply different between Icelandic and Italian couples, as the former turned out to manage the temporal organization in a more synchronous and regular way than the latter. Furthermore, peculiar gestures were recognized for Icelandic and Italian couples, underlining systematic differences in the cultural framework. The same research group published a study where T-pattern analysis was utilized to assess the involvement of the subject in affective interaction with virtual agents (Agliati et al., 2006a).

During the last few years the amount of research using *Theme* in problem solving, ergonomics and group interaction situations has increased significantly. Studying gender at work, using eavesdropping on communication patterns in two token teams, Koch et al. (2005) assessed patterns of talking times, back channeling, gaze behavior, affect display and movement qualities. The results suggested patterns within and between verbal and nonverbal codes and supported and exemplified research findings that gender-token status frequently has negative consequences for women. Koch (2007) also used *Theme* to study conflict patterns in group communication. The research evaluated talking times, gaze patterns and movement qualities with a particular focus on verbal and non-verbal codes. The author showed that the T-pattern analysis has been able to preserve the complexity of the original behavior data allowing, at the same time, an integrative perspective at verbal and non-verbal patterns.

Using temporal patterns to derive stress factors of routine tasks was the subject of Brdiczka et al. (2009, 2010) studies, reporting on detected T-patterns and derived correlations with participant perceptions of workload, autonomy, and productivity. The same research group has more recently showed that T-patterns of interactions with computational media are very important indicators of facets of routineness and that these measures are correlated with the affective states (Su et al., 2013). Stachowski et al. (2009) analyzed the benefits of flexible team interaction during crises using *Theme*, which revealed systematic differences among crews in their patterns of interaction. Mean comparisons and discriminant function analysis indicated that higher performing crews exhibited fewer, shorter, and less complex interaction patterns. These results illustrate the limitations of standardized response patterns and highlight the importance of team adaptability. With emphasis on early interaction patterns in swift-starting teams as a predictor of effectiveness, Zijlstra (2012) reported that the effective teams exhibited patterns that were more stable in duration, more stable in complexity, and more reciprocal as compared to those of less effective teams.

Borrie et al. (2002) published a paper on temporal pattern analysis and its applicability in sports. The paper outlined a new approach to the analysis of time-based event records and real-time behavior records on sport performance. Exemplar data from the analysis of 13 soccer matches was presented to highlight the potential of *Theme* analysis. The results from the soccer suggest that it is possible to identify new profiles for both individuals and teams based on the analysis of temporal behavioral patterns detected within the performances. Since then there has been a significant increase in the application of *Theme* in sport research and movement science, including research on soccer (Anguera-Argilaga and Jonsson, 2003; Anguera-Argilaga et al., 2003; Jonsson et al., 2003, 2004, 2006; Bloomfield et al., 2005; Camerino et al., 2012; Lapresa et al., 2013a,b), motor skills, dance and body movement (Castañer et al., 2009, 2010a,b; Torrents et al., 2010), martial arts (Gutierrez et al., 2009, 2011), basketball (Fernandez et al., 2009) and swimming (Louro et al., 2010).

Theme has also been applied in several projects in robotics and artificial intelligence. Kerepesi et al. (2005, 2006) conducted a behavioral comparison of human–animal (dog) and human–robot (AIBO) interactions. The authors claimed that behavioral analysis of human–robot interactions can help in developing socially interactive robots. Although the number of interactive T-patterns did not significantly differ among the groups (children and adults), the partner's type (dog or AIBO) had a significant effect on the structure of the patterns. Both children and adults terminated T-patterns more frequently when playing with AIBO than when playing with the dog puppy, which suggest that the robot has a limited ability to engage in temporally structured behavioral interactions with humans. As other human studies suggest that the temporal complexity of the interaction is good measure of the partner's attitude, the authors suggested that more attention should be paid in the future to the robots' ability to engage in cooperative interaction with humans.

T-pattern analysis of human–cat interaction has been carried out by Wedl et al. (2011). These authors demonstrated the existence of complex patterns emerging from the dyadic interaction of a cat with its owner. Interestingly, the authors showed that in dyads with a female owner, the number of detected patterns was noticeably higher than in dyads with a male owner.

Jonsson and Thorisson (2010) have been using *Theme* for evaluating multimodal human–robot interaction, as reported in their case study of an early humanoid prototype. Providing robots with human interactive skills is a challenging and worthy goal and numerous efforts are currently underway; evaluating the progress in this direction, however, continues to be a challenge. In this paper the authors use *Theme* to evaluate human–robot multimodal natural behavior in a case study involving a virtual robot prototype, Gandalf, which is capable of real-time verbal and non-verbal interaction with people. The analysis includes a comparison to a comparable human-human dyadic interaction scenario. The main objective being to develop a methodology for comparing the quality and effectiveness of human–robot interactions between wide varieties of such systems. Early results indicate that the approach holds significant promise as a future methodology for evaluating complex systems that have a natural counterpart. Table 1 summarizes various applications of T-pattern analysis, with their respective references, in the study of human and animal behavior.

6. Conclusion

The present review has focused on a multivariate technique known as T-pattern analysis. By means of this analytical approach repeated sequences of behavior can be appraised and analyzed. Several methodological and conceptual highlights of T-pattern analysis have been discussed as well. In addition, by offering a synopsis on the current literature on this subject, this work represents a useful background for researchers who intend to employ such a refined multivariate approach in the study of behavior.

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