Segmentation of Tunisian Modal Improvisation: Comparing Listeners’ Responses with Computational Predictions

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Abstract

This study is aimed at an exploration of segmentation strategies through a comparison between listeners’ reactions and predictions estimated using computational models. In a listening experiment, Tunisian subjects of various degrees of expertise were asked to listen to a traditional Tunisian improvisation and to indicate in real time the perceived segmentation, first on a global level, and then on a more detailed level.

In parallel, the same piece has been transcribed and analysed by computer, based on heuristics of local discontinuity and parallelism. A detailed analysis of the possible mapping between listeners’ responses and models’ predictions suggests an explanation of the factors underlying the listeners’ understanding of modal improvisation. Most of the segmentation positions proposed by the subjects can be partly explained by the presence of local discontinuities along time and pitch dimensions. Strong local discontinuities relate to listeners’ segmentation decisions; weaker discontinuities, on the contrary, cannot explain the perception of segmentation unless they are combined with other factors such as parallelism. Segmentation by Tunisian listeners can be approximated using a model combining local discontinuity and parallelism.

1. Introduction

This paper presents an interdisciplinary project involving musicology, experimental psychology, music cognition and computer science. The objective of the study is to explore the cognitive factors underlying the structural understanding of improvised modal music using one particular musical example: a Nay flute Istikhbâr improvisation performed by the Tunisian master Mohamed Saâda.

The study will focus on one particular aspect of musical understanding: namely, segmentation, i.e. the spontaneous decomposition, by listeners, of the musical flow into segments. The general aim of this study is to try to clarify segmentation strategies by comparing listeners’ reactions with segmentation estimated using computational models based on local segmentation factors and parallelism.

The segmentation heuristics can be classified according to their dependency on pre-existing knowledge, the abstraction of this knowledge, and the temporal extent of underlying retentive processes. Low-level features are embodied in acoustic properties of the musical surface (pitch, timbre, intensity, duration) whereas high-level features rely on learned schemata. The long-term objective of our study is to understand the complex interaction between processing based on sensory data and processing based on learned knowledge.

In the study presented in this article, schemata will not be considered in their broadest generality, but will be restricted to motifs, i.e. schemata simply defined by a succession of notes. In order to establish clearly the interrelations between the different factors explaining segmentation strategies, various heuristics are formalized and systematically applied to the musical material by means of computational modelling.
2. Background

2.1 Background in cognitive musicology

A bic mic he can bene f m ne e e ci e n m ic nde anding e ed b ch l gical and c gn i e e ca ch (A a i & McAdam, 2003). In a ic la he e ci e n f m ical c ema be e e i nh he hel f Ge al he, he ie f m ic egmen a i n and hie a ch (e.g. Le dahl & Jackend , 1983).

Pa ic la e i n el a e he in e ac i n be een c l e and na e in m ic nde anding and he im an ce f em ala ehen i n f m ic (Imbe , 1981). The e ci e n can be in e iga ed b d ing h li e ne f m di e en e c l e egmen im i ed m ic, g ided in a ic l a b m dal an i i n, m dal el i n (Bigand, 1993), and h he ge i el c n c in a all el a gl bal m ical meaning. One a ic la bjec f in e i gn a deal i h h e cgni i e ce e enabling he ec gni i n egmen a i n in and em al in eg a i n (A a i , 2005).

One f he h he nde ling hi in e di ci lin a jec i ha a e a able ac i a le a n chema a hich hem el e ma a ec, in e n, he d namic ce egmen a i n. The e f, he e i a c m le in e ac i n be een he an anal i f he in da a and he in ence f c l al kn ledge in he a a gi en m ical e ence i gani ed. Hence, e m b e e hi ce f m di e en e c e i incl ding m ic anal i, c gni i e e h n m ic l g and c m e d m dell f m ical a e n iden i ca i n, in de de c i be he eal ime enal f m ic nde anding.

2.2 Background in computational music analysis

D ing he la ce n , m ic l g ha f m la ed he need f me h dl gical e lan a i n f m ic anal i (Re i, 1951). S ema ic a em nde aken in a ic la b ling i ic and em i c (R e, 1987; Na i, 1990) ha e been ha m ed b he nde ling c m le i f ible a egi and c c e. F mali ed d e ci i n egmen a i n a egie e ed b ch l gical and c gni i e die migh be ible ed a amen g ide and make e li d i e c e ce. In addi n, c m a i, nal m del (Camb l, 1998, 2001, 2006; R lland, 1999; C nklin & Anagn l, 2001; Me ed i h e al , 2002; B d, 2002; La ill , 2005; Ahlback, 2007) enable e ha i e anal e f i e e b m ical i ec e, b ill ggle c n l he c mbina e l i n f c e and em i cal ele an anal e. I eem nece a in a ic la n eil he di e en fac e n ible f ch d i e ge nce and b ild ge i el ac m le em e e ng en li ene e ec ai n (La ill , 2007). In hi e ec, li ening e i men igni can l c n ib e a ge i e im emen f he m del.

2.3 Segmentation heuristics

A a i (2005) e a n n-e ha i el i f he i ic ling he e ci e n f egmen a i n hen li ening f m lae-ba ed im i ed m ic, and hic h can be gani ed in h ee di e en cla e.

(a) Fac de ending minimall n acc la i n, ch a:

- (a1) Di c n i in ie be een a di a ib e: an igni can de a e, f a gi en m ical a am e f m a d main f al e i h hic h a gi en eam f n e c m lie de a e ch a a i ch lea, a change f imb e, a m di ca i n f nd de el, f em al ha e f ndi id al e en, f h h mic al e, e c, end im l egmen a i n, in line i h he Gestalt he inci le f imila i and imi (Le dahl & Jackend , 1983; Deliege, 1987).

- (a2) E ac i n and mem a in f ce ea ed a e n: a ic la cheme, cha e ence f i che, h hic h mic al e, e c, a e ec ei de a h le e i e, all called a e n, if he a e ea ed e e al ime, de el ed h gh he ice, ih ih a a i i n. Thi c e nd he inci le f a al lel i m (Le dahl & Jackend , 1983). A la ge a f m ical c e highlight ed b m ical anal i, ch a m if and me ical c e, eme ge f m he de ec ed e e i n f a ic la a e n. The a f m i c a e n, in a ic la i, el a ed hei em al an: l cal e e f cell, hema ic igna e f m if, able e i ia n f ha e, c al nc a i n f h le a e e i i n.

(b) E en abili in el a i n a f c i nal hie a ch be eena ib e: am ical hae end end na cale deg ee hu i hie a chicall ei (he nie in We e nali, he i n e he fan A abic Maqm) and e c e ed a m e able. Ending nal e able n ec e e a feeling fine m le i n f m ical en i a. A ill a ed b he el f he d ca ied b Bigand (1993), li ene end e c e a egmen a i n in hen a mel dic ha m nic e ence e le in a able n. Simila e ec a i e hen e ec i lie ene egmen A abic Maqm it (A a i, 2005). D e he de en dence f hi e f indica n ca l al kn ledge, he e l a ee ec ed a acc ding li ene ' c el al i gri n.

(c) Fac higl de enden nli ene ' kn ledge, ela ed m de and ef mance le a el a ci c ala ec.

- (c1) M d la i n be een m de, nali i e: Maqm, n hic h hi di cen ed, i a m ical le e en ilal de e mined b i m dal
structure (Figure 1), which provides a scheme guiding the elaboration of improvisations in this style. This modal structure is understood by expert musicians and listeners as implicitly made up of the juxtaposition of musical 'Iqdgenres, which are characterized not only by scales (i.e. particular set of pitches), but also by emblematic melodico-rhythmic motivic formulae. Figure 2 shows for instance a formula-pattern central to the Mhayyer Sīkāgenre that will be studied in our experiment. A recognition of a genre-specific motivic formula triggers a transition between genres, producing a segmentation at a relatively high level of the hierarchy. An analogue (but not identical) to this phenomenon in western music would be a change in tonality or a harmonic modulation.

Formal and stylistic schemata: The high-level schemata discussed in this last category are linked to the musical process and to melodic introduction, exposition, development, recapitulation, and closing gestures specific to a given musical structure such as a Taqsīm, a sonata, a minuet, etc. These large sections, and parts of these sections, are often characterized by prominent harmonic or modal modulations that only listeners from that culture are able to follow. When listening to a piece of music within a given cultural context, expert listeners tend to partly follow a strategy based on the structural organization of the piece. The cognitive schemata that are activated prompt a more focused observation, which anticipates what should happen next. These expectations can be more or less precise depending on the style of the piece, the performer, and the culture in question.

3. Listening experiment

3.1 Objectives and hypotheses

The objective of the experiment is to broaden our understanding of listeners' segmentation strategies through a comparison of listeners' segmentation decisions—collected via listening tests—with segmentation prediction generated by cognitively-grounded computational models. Due to the complexity of the problem and the limited scope of the computational models, in this experiment we test whether, and to which degree, listeners' segmentation can be explained by heuristics based uniquely on local discontinuities and pattern repetitions. Although this reduction in the scope of the model probably implies a simplification of the study and the suppression of subtle
b im an a ec, e h he i e ha he ed ed c i ni f c n f ndamen al c gni i e mechani m c ld e eal in ee ing c nel i n, a dic ed a he end f he a ic e.

3.2 Stimulus

The e e im i l i a i d i a i nal T ni i an Istikhbār im i a i in la ed na a di i nal e, called Na, b M hamed Saada, h a a c nd c, c m e, and fe a T ni Un i e i. We a me ha e e li ene ill ha e n di c l egmen ing an im i a i in ha f l a adi i nal le. The Istikhbār im i a i ne li c l de el he f ndamen al elemen f he Mhayer Sikā D m de (Fig e 1). The an c i n f he im i a i n, hich ill be ed f he c m a i nal anal e, i h ni in Fig e 7 (a) and (b), Sec i n 4.4. The im i ed mel die f hi Istikhbār a e made f mel dic m if ha e e en m dal chema a e c i c Tba’ Mhayer Sikā. The gani a i n f her m ical c eadhe e he cheme adi i nall ed; he ignali f hi an c ibed im i a i ni e e ed in he a ic la a he mel dic m emen a e a ic la ed ne i h each he.

3.3 Listening test

T en e e T ni i an li ene f m he High In i e f M ic f S e, T ni ia, a ici a ed in he e e i men. The e m i c i an (in men al, in ge, and c m e) a e eachen and den, and la b h adi i nal and m de n T ni i an m ic, a ell a A abic m ic in gene al, We en m ic, ja, e.

In de d le he e li e’ di e ce c e f egmen a i n and ec gni i n, a e i f ak ee de i gned. The f e he e imen ha i cen al he e e n el a e he e de mi a i n f egmen a i n a e gie.’ The e e l f egmen a i n ce c i de ed. In de c e he m ical ma e ial eal im, bjec e e f ee che and change a an ime he egmen a i n c i e i a and he hie a chical le e le c n i de ed a i a ed ing he and ec nd egmen a i n ha e.

- Li ene e e ked egmen he Istikhbār in hae ha ee am al ical che en a ible and indic e he lace he e he ece a egmen ed, a ee al indic e ed, d ing a ee nd li ening, he in a f an i i n be een c ec ie hae. Li ene e ed a ke a ke b bad hile e ball de c ibing he im i a i n. A g am a ed nch nie he a di e ence, he ime di la, and he ec ding f

he e bal e nece nding each egmen a i n i.
- Li ene e e hen a ked egmen he hae in m if hile ee cif ing hei ela ed m ical f n c i n i hin he e a ell c e f he iec e.
- A hi d egmen a i n a i n ed a d he de ec in f m dal an i i in be een he a ‘Iqd gen e. Thi a k i in died f he in hi e, an c m a i nal m de la been de ed f hi a ic la ic.

Fll ing hi egmen a i n a k, ine ie ih he li ene e ca i ed , in de ine e he li ene ’eac i n, nde and he d i c l ee e i enced b li ene d ing he ideni ca i in, ed c i n, and egmen a i n age, and nall c n a di e e en li ening a egie c n i b ing he eal ime ee i n f am ical k.

3.4 Analysis of the empirical data

3.4.1 First segmentation task

Fig e 3 h he e e f he T ni i an li ene he egmen a i n a k. F e am le, bjec N .11 egmen ed he iece in a (den ed A and B and h ne ee c i el in Fig e 7 (a) and (b), Sec i n 4.4), hile bjec N .3 egmen ed i i in 19 ec i n. Thi indica e ha he T ni i an li ene did n all e he ame c i e ia hen egmen ing he iece (A a i, 2008).

In de nde and be e he bjec ’e ne d ing hi egmen a i n a k and be e h bjec ge i el gan ei he d nam i c e f he im i a i n, e ne ca i ed ih imila e e ee c d ed. A he ame ime, a efeence anal ia a ca i ed b an e e m ic l gi , h, c n a he bjec f he e e i men, died he anc i i n bef chand a a ed he ibili li en he im i a i n a man ime a needed. We h he i e he ha b h m i c l gi and bjec e he ame e f egmen a i n he ic men i ned ea lie. On he he hand, he efeence egmen a i n gi en b he m ic l gi, ince n c n ained b eal ime limi a i n, i c n ide ed a m e b and m e acc ae em all. Indeed, li ene ’egmen a i n cca i nall a ea ed bef eb m e f en af e he efe en ial a ic lain in indica ed in he m ic l gi ‘anal i f he anc i i n. S me T ni ian bjec e e able fll he a ic la i n he e f me ’le, iden if he d nami m in he de el men f mel die and he ef e an ici a d he c n i n a i n and he c n cl i n f he m ical di c e. On he he hand, a la ge n mbe f bjec eac ed la e beca e he ai ed f he beginning f he

1F hi ean, he ak f i den i ca i in and ed c i n (cf. A a i, 2008) ill ne de di ed he e.

2Namel, he ec nd a h f hi a ic e.
The X-axis represents the time progression of the piece in seconds and the Y-axis represents the subject ID number. Dots correspond to segmentation points indicated by each subject while listening to the piece in real-time. Vertical lines delimit the major sections of the improvisation according to the musicologist’s analysis.

3.4.2 Second segmentation task

Similar to the first segmentation task, the responses to the second segmentation task by the Tunisian subjects are shown in Figure 5. Figure 6 shows general trends in the Tunisian subjects’ second segmentation, indicating the number of reactions corresponding to similar musical percepts at precise moments during the improvisation. Here again, responses are regrouped and repositioned according to the musical descriptions they relate to. This analysis makes it possible to observe the organization of the internal structure of the improvisation as described by the 20 Tunisian subjects. The most relevant articulation points in the improvisation and the subsections that organize its structure were perceived at the same time by a variable number of subjects (3 to 17 subjects). The temporal positions of the segmentation points, after clustering, and the number of subjects reporting each of these segmentation points will be used for the final mapping with the model predictions, as shown in Figures 7 (a) and (b), Section 4.4.

4. Computational modelling

In this study, as a first approach, among the five different segmentation heuristics described previously, only three of them will be taken into consideration in the proposed modelling, namely:

Fig. 3. Responses of each Tunisian subject to the first segmentation task. The X-axis represents the temporal progression of the piece in seconds and the Y-axis the subject ID number. Dots correspond to segmentation points indicated by each subject while listening to the piece in real-time. Vertical lines delimit the major sections of the improvisation according to the musicologist’s analysis.
Discontinuities between auditory attributes (heuristic a1): this relates to sensory appreciation of the surface level.

Parallelism (heuristic a2): also stemming from the surface level, but requiring memorization processes.

Fig. 4. Global overview of the Tunisian subjects responses for the first segmentation task. The X-axis represents the temporal progression of the piece in seconds and the Y-axis the number of subjects. Reactions have been clustered into underlying musical percepts, according to the descriptions provided by the Tunisian listeners, such as: 'end of melodic movement', 'section ending', etc. Vertical lines delimit the major sections of the improvisation according to the musicologist's analysis.

Fig. 5. Reactions of each Tunisian subject during the second segmentation. See Figure 3 for a description of the axes.

- Discontinuity between auditory attributes (heuristic a1): this relates to sensory appreciation of the surface level.
- Parallelism (heuristic a2): also stemming from the surface level, but requiring memorization processes.

Pa allelism (he ic a2): all emming f m a1); hi ela en a ecia in f he face he face le el, b e i ng mem i a in le el.
Specific melodic-rhythmic patterns related to modal 'Iqd-genres (heuristic c1): although pertaining to high-level structures depending on cultural knowledge, we will hypothesize in this experiment that they can be inferred directly from the piece itself via the parallelism heuristic. This section details modelling strategies for these types of segmentation.

4.1 Modelling local segmentation

As explained in Section 2.3, local segmentation is based on relatively contrastive discontinuities along one or several musical dimensions (usually temporal distances and pitch intervals between notes). This rule follows the Gestalt theory principles of proximity and similarity. The computational model employed in this study is Cambouropoulos' (2001) Local Boundary Detection Model (LBDM), which is based on two rules, a Change rule and a Proximity rule, that calculate boundary strength values, for each interval of a melodic surface, indicating the relative importance of each successive local discontinuity. The resulting segmentation points are valued from 0 (absolutely continuous) to 1 (extremely discontinuous). The LBDM has been chosen as it has been shown to perform rather well (de Nooijer et al., 2009). For comparison, an analysis using Tenney and Polansky's (1980) model was also attempted, without offering any significant corroboration with the experimental data (Lartillot & Ayari, 2008). Both LBDM and Tenney and Polansky's models have been tested using the implementations available in the MIDItoolbox (Eerola & Toiviainen, 2004).

4.2 Modelling parallelism

Concerning parallelism, the motivic structure of the improvisation has been analysed in details through computer-based motivic pattern extraction. Several algorithms have been proposed in the literature (see overview in Lartillot, 2005, 2007). In order to reduce the combinatorial explosion of results produced at the pattern extraction phase, most algorithms employ filtering heuristics that select a sub-class of the resulting patterns based on global criteria such as pattern length, pattern frequency (within a piece or among different pieces), and so on. The main limitation of this method comes from the lack of selectivity of these global criteria. For instance, by selecting longest patterns, one may discard short motifs that listeners may nevertheless consider as highly relevant. And conversely patterns repeated even only twice may be perceived if these repetitions are sufficiently close in time, such that the first occurrence is still kept in the short term memory — and therefore easily recalled — while the second occurrence is heard.

Fig. 6. Global overview of the Tunisian subjects response during the second segmentation, after data clustering. See Figure 4 for a description of the axes.

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Combinatorial explosion can be caused by another.

Heuristics have been added for the taking into specific descriptions: thanks to an adaptive and lossless selection of most the pattern configurations without loss of information, propose heuristics ensuring a compact representation of building as simple a model as possible that may be able hampering the efficiency of computational models, and at discovering the origins of the combinatorial explosion (Lartillot & Toiviainen, 2007) is primarily aimed at.

The model developed by the first author of this paper concept of mental to the effectiveness of the algorithm. The (Cambouropoulos, 1998) and is known to be detri-

perceived due to their complex intertwining combinatorial explosion of patterns that are not identical to the first description of the pattern. This pattern can be extended by a description that is followed by the beginning of a new occurrence, each occurrences of a single pattern. As each occurrence is common phenomenon provoked by successive repeti-

lence on the surface level.

of these heuristics, pattern repetition can be detected deep structure of these sequences. With the addition revealing the sequence of pivotal notes forming the level of musical sequences, musical transformations that automatically discover, from the raw surface and pitch dimensions. We are developing algorithms in the neighbourhood of primary notes, in both time improvisations, where secondary notes can be added mentation, which are very common in Arabic modal consideration of melodic variations such as orna-

3.12.

The motivic pattern extraction algorithm, when applied to the music studied in this article, should nevertheless be considered with the first state of the following occurrence, suggested an interesting insight regarding the percep-

4.3 Inducing segmentation from parallelism

The music, acenas alalg ihim, hen a lied he Istikhbär im iain, highlighted he e fne ha ae cni de ed a e ed a en (ee he an c i in e in Fige 7 (a) and (b), Secin 4.4). In the a l he eel in e i gain cen ed n he e i f f egmen ai n, he aen need be an la ed in egmen ai n in S die he a e gge ed ha beginnin f a e a en e likel igge egmen ai n deci i han ending, incending a en gene all m e a ec ed b mel dic a ı a i n, e ling in amedi c l de e ci n f hei e minai n (Camb 1, 2006). One main -blem he es i ha in a eal ime li ening c ne, he de ec i n f a e n hem el e i in an any e, a i gene all e i he be a i n fa lea me f he m ical cm nen cha ac e i i h ing he a e n. The ef e, nle he a en i al ead ec ed, fea a e cha ac e i i ic beginning, a egmen ai n can ha dl be ind ced a i beginning.5 F hi en a n, in hi d, nl a en ending ill be aken in c ni de ai n acie i f egmen ai n.

In he ca e f clic a e n, he he e ei n immedi a f l l each he, egmen ai n can be m e blema ic. Acc ding he m aigh f -a d h hei, egmen ai n migbe be ec ed a b de, imila l ac clic a e n. B de he c nca ein f ee i i n, he eb de mig h n in me ca be e ce ible an me (nle l cal b nda ie e a l a he i n).

In hi d, e gge an he he ic f egmen ai n ind e i na ba ed n propagation of segmenta-
tion expectations: d in g he e e i i n f a a e n, egmen ai n de ec ed in ei cc encef i e e ec ed a ea d ing he ng ing cc ence a ell, in he a me ha e Segmen ai hai a ga ed in hi a elie nl cal b nda ie, i ind ced b he aen incl ded in he e clic a e n. One in e e i ng c ne ence f hi a adigm i ha , d e he im lied e eca i n, n nl he ending f he incl ded a e n, b al he a ing in can be ch en a ible can de e f egmen ai n.

A e i n f he cm ai n anal i a e en ed in La ill and Aai (2006), b ih ac alc ma i n h he li ene egmen ai n.
4.4 Explanatory mapping between observations and predictions

Figures 7 (a) and (b) show the analysis of the complete improvisation both by the subjects and the computational implementation of the models. The subjects' responses are displayed above the staves using downward triangles of two colours: black for the first higher-level segmentation, and white for the second more detailed segmentation. For each location the number of subjects who segmented at that particular location is indicated. As mentioned above, due to the real-time context of the experiment, segmentation points have been relocated based on the listeners' own justification of their segmentation choices.

4.4.1 Impact of local segmentation

Local segmentation predicted by the LBDM model is displayed below the staves with upward triangles, and associated strengths are indicated below each triangle. LBDM segmentation offers good congruence with listeners' segmentation: all segmentation points with strength equal or superior to 0.25 are corroborated by some of the listeners. All the other segmentation points proposed by the subjects (except one, mentioned below) can be related to LBDM segments of lower strength, but the selection of these points cannot be explained using the LBDM alone. Other segmentation factors will be used to select, among the low-strength LBDM segmentation points, those that can explain listeners' choices.

4.4.2 Impact of parallelism

Patterns extracted by our algorithm are displayed below the staves with horizontal lines; vertical marks indicate the implied segmentation points, and letters from a to e denote the corresponding motivic classes, as described below. Several phrase-like patterns, noted I, II and III, are circled on the staves.

The termination of acyclic patterns, indicated by lines under the staves showing only one vertical mark at their right ends, contributed to listeners' segmentation. The most typical example of such patterns is the archetypical Mhayyer Sıˆkaˆ motif (pattern a, cf. also Figure 2). Each termination of this pattern provokes a segmentation decision by listeners, even when local boundary strength is low (under 0.25). An extreme case is shown at the end of the improvisation.

Fig. 7. (a) Transcription, analysis and segmentation of Mohamed Saâda's Istikhbaˆr by Tunisian listeners (over the staves) and by computer (under the staves). See Section 4 for an explanation of the annotations. This figure shows the first part of the improvisation. (b) Second part of the analysis of Mohamed Saâda's Istikhbaˆr.
5. Discussion

A he anal i ha n, he T n ian li ene', egmen ain f he Istikhbâr im iain can be e lained a large en ing ema ic m del f mali ed and im lemen ed n he cm e. M egmen ain in infe ed b T n ian li ene can be a l e lained b he e ence f l cal di c n in i al ng ime and i ch dimen i n. S ng l cal b nd-aie can be ea il ela ed li ene' egmen a i n deci n; c ake b nda ie, n he c n a, aen ci en e lain he e e i n f egmen ain nle he ae ed b he fac ch a a lelli m. M egmen a i n f m T n ian bjec f he Istikhbâr im iain can be e lained in em f in e de endenc e be een l cal b nda ie and a a lelli m, ha e ed f malic ing a he i i c f again f egmen a ine e cai n. Thi me aci ne lain a c mm n c mm nica i n inci le in i i el ed in m ic ef mance: nce a a ic la m ical idea ha been clea l e ed (ch a he e e i i n f m if c), i b e e n e e i nd ne i e he a me a en i n b h f m e f me and li ene (and e f n m h c m e, hen en ide ing i en m ic), a he c al c en f he a en ha been al ead in d ced and nde d.

The di en le el f egmen a in a inf ed b e e T n ian li ene can h be e lained ing a m del ha a in iial deigned f hi e f m ic, b i ba ed n gene a c gni i e mechani m ch a l cal di c n in i e and a a lelli m. H e e, a me e ci e cai a i n f egmen a ine le e i e aking in acc n he c l al fac in encing egmen a in: f cni nal hie ach be een a ib e and he im lied e en abili, he e all m dal c e (a ill a ed in Fig e l), fea ing b h cale and ha c m n en, and highe-le el f mal and li ic chema a. The c m a in al m delling f he c m le egmen a in ce ld gge a ema-ica e men f he m del ba ed n he c ng ene i h he li ene 'ene c, e ring hence a ne c nce al f a me k A abic m ic g.

The nal bjec i ef f he jec in he f e i h de e mine he in ence f c l al kn ledge n he e ce i n and nde anding f a icce f m ic, and he le f nie al gni i e ce e. O aim i be e a ic la he e a ec h gh he de ign f a c m le m del in e g a ing b h c gni i e ce e c l al kn ledge, in de de el he a cia i n f egmen a ine egie b li ene f ai c l al backg nd (A abic, E ean, e c). We e c e he ca e f l m delling f hi c l al kn ledge ill enable di e en ia e ci el be een he e n ef T n ian and n n-T n ian m ician.6 The e ling

6An e en i n f hi d (A ai, 2008) h in a ic la ha egmen a ine in f ed b E ean m ician el e c ni enc, al h gh J a m ician eem e be able g a maj a ec f he hual and m dal en e i n f he im iain. F he e imen al da a ha e been c llec ed, in de e c i el he deg ee f e enence f he c gni i e cheme ed b T n ian li ene hen anal ing in eal-im em d en im iain ba ed n en em a le.
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