DEVELOPING CAPACITY AND MUSIC COGNITION IN CHILDREN: RELATIONAL COMPLEXITY AND TRANSITIVE INFERENCE USING PITCH AND DURATION

Kate Stevens
Melinda Gallagher
MARCS Auditory Laboratories, University of Western Sydney-Bankstown, Australia

ABSTRACT

Background. This experiment investigates an aspect of Halford's (1993) theory of cognitive development in the auditory domain. Halford conceptualises the development of children's thinking and understanding as an increase in cognitive capacity and ability to deal with problems of increasing relational complexity. Relational complexity refers to the number of independent relations that need to be processed in parallel to solve a problem or complete a task. Working with visual, spatial and verbal stimuli, Halford and his colleagues have demonstrated that children aged one year can perform unary level tasks, at around two years can perform binary level tasks, by age five can perform ternary level tasks, and by age eleven most can accomplish quaternary level tasks.

Aims. The aim of the experiment is to test predictions of Halford's theory of cognitive development in an auditory context.

Method. Patterns that differed in relational complexity were composed and presented to children in the form of analogical reasoning and transitive inference tasks. The sequences consisted of pitch- or duration-based relations.

Results. As hypothesized, children's ability to perform the tasks of increasing relational complexity was predicted by their age. Additionally, duration-varying patterns were responded to less accurately than pitch-based patterns at unary and binary levels.

Conclusions. The results support a mental models view of cognitive development and the relevance of relational complexity, processing load and conceptual chunking in audition. Theoretical and practical implications for considering auditory cognition in general, and music perception, production and learning in particular, in terms of relational complexity and chunking, are discussed.

1. INTRODUCTION

We propose a new and integrated approach to studying the development of musical understanding based on Halford's (1993) theory of cognitive development. The essence of Halford's (1993) view of cognitive development relies on the notion that children's thought can be considered in terms of mental models and the operations on them. We demonstrate that the developmental order of sensitivity to musical dimensions and tasks (e.g. Hargreaves, 1986; Shuter-Dyson & Gabriel, 1981) is explicable using concepts of relational complexity, processing load, and conceptual chunking.

1.1 Halford's Theory of Cognitive Development

Halford's (1993) theory of development provides a testable and explanatory framework for analysis of children's understanding of musical patterns. Understanding, Halford argues, entails having a mental model that represents the structure of a concept or phenomenon. Mental models are representations or a representation as a mapping from a symbol system to an environment system (Halford & Wilson, 1980). Representations differ in their dimensionality and a strength of Halford's approach is the specification of a complexity metric based on the dimensionality of a concept (Halford, Wilson & Phillips, 1998). Dimensionality is defined as the number of independent units of information required to represent the concept. One-dimensional concepts are defined as predicates with one argument, or as unary relations of the form r(x). Category membership, such as CAT(Max) asserting that Max is a cat, is an example of a unary relation. Two-dimensional tasks are defined as predicates with two arguments or as binary relations, r(x,y). An example is the binary relation LARGER THAN(elephant, dog). Three-dimensional concepts consist of predicates with three arguments or as ternary relations, r(x,y,z). Transitivity or a set of ordered triples, such as Jim is happier than Paul, Paul is happier than Dave, so Jim is happier than Dave, is an example of a three-dimensional concept expressible as a ternary relation. Four-dimensional concepts are defined as predicates with four arguments or as quaternary relations, r(w,x,y,z). An example is a composition of binary operations such as $a(b+c) = d$. The proportion a/b = c/d is a quaternary relation and entails relations between the four terms a, b, c, d (Halford, Wilson & Phillips, 1998).

Many cognitive tasks involve the processing of relations and cognitive capacity limitations in children (and in adults) can be defined by the complexity of relations that can be processed in parallel (Halford, 1993; Halford, Wilson & Phillips, 1998). A problem becomes more complex as the number of interacting factors increases – complexity can be measured by the dimensionality of the relation or number of variables that are related. Problems that entail a binary relation are simpler than those that entail a ternary relation, ternary relations are simpler than quaternary relations.

ISBN 3-931852-67-9
ISSN 1617-6847

1.2 Constructing Auditory Tasks of Differing Levels of Relational Complexity

A unary relation consists of a mapping of one dimension and can be of the form A:B. A visual task involving a unary relation might involve comparing two different coloured blocks and deciding if the blocks are the same or different (Halford, 1993). An auditory unary level task will involve two differently pitched sounds and judging whether the notes are the same or different. A binary relation such as "larger than" has two arguments, for example, cat is larger than kitten. A binary analogy is of the form A:B::C:D as in kitten is to cat as puppy is to dog. The relation must be taken between A and B and mapped or recognised in C and D. An auditory binary level task could require a listener to segment sounds into groups which are similar and which occur regularly (Drake, Dowling & Palmer, 1991; Handel, 1974). In the present study, a binary task involves the participant listening to a pitch pattern of four sounds split into patterns of two and deciding whether the second pattern is the same as the first.

More cognitive resources are needed to mentally manipulate and process ternary relations as they involve three arguments. Transitive inference tasks take the form of a three argument problem; for example, A>B, B>C, therefore A>C. An example of the three step process involved in a child processing a ternary task could be mapping blocks to sticks which also differ in colour. The child must extract the colour of the pattern, map blocks to sticks, and decide whether the pattern of coloured blocks is the same as the pattern of coloured sticks. An auditory ternary level task could be listening to a six note sound pattern and establishing an order of the sounds, mapping the first note with the second and third, and deciding if the pattern fits the ordering rule.

Maximum processing capacity is required for processing quaternary relations, that is, virtually all resources are needed (Halford, 1993). A quaternary relation involves four arguments. A quaternary task in vision would involve once again matching colour, using sticks and blocks but there could be an added dimension of the blocks set up in a tower and the sticks set out in a row. This is a quaternary task as the colours would need to be in order with each other, there is the encoding of matching sticks to blocks and also an up-down processing order (the tower of blocks) to a left-right processing order (the row of sticks). An auditory quaternary level task, could be the same as the auditory ternary task, with the addition that the listener might be required to apply independent rules for, say, both loudness and duration of each particular sound.

1.3 Aim, Hypotheses, and Design

The aim of the experiment was to test assumptions of Halford's (1993) theory of cognitive development in audition. Halford posits that the minimum age at which children can master cognitive tasks can be analysed using the amount of information that needs to be used in the task decision. Children age 1 and below can perform unary level tasks, at around 2 children can perform binary level tasks, by age 5 they are able to perform ternary level tasks, and by age 11 most can accomplish quaternary tasks (Halford, 1993). In the present study, 5-, 8-, and 11-year old children were tested. It was hypothesized that all age groups are able to accurately complete unary and binary level tasks, that 8- and 11-year old children have mastery of ternary level tasks, and that 11-year old children have mastery of quaternary level tasks. The 3 x 4 x 2 experimental design comprised the independent variables age (5 years, 8 years, 11 years), relational complexity (unary, binary, ternary, quaternary) and feature (pitch, duration), with repeated measures on the latter two factors. The dependent variable was accuracy.

2. METHOD

2.1 Participants

Participants were 86 students from local state schools in South West Sydney. There were 27 participants (10 females, 17 males) aged 5.0 years to 5.11 years (M=5.07, SD=.03), 28 participants (13 females, 15 males) aged 8.0 years to 8.11 years (M=8.06, SD=.04), and 31 participants (14 females, 17 males) aged 11.0 years to 11.11 years (M=11.07, SD=.03).

2.2 Materials

The pitch and duration trials of different levels of complexity consisted of consonant, novel sequences of pure tones. The tones were selected from the octave above middle C. For the pitch trials, note duration was held constant at 300 ms and pitch differences were intervals of a third. The duration trials consisted of tones with lengths of 150ms, 300ms and 600ms with frequency held constant at 440.0Hz. The relative tone lengths were equal to quarter-, half- and whole-note durations and should have exceeded the just noticeable difference for duration. Amplitude was constant throughout trials.

The pitch and duration trials consisted of the four levels of relational complexity (unary, binary, ternary, quaternary), and practice trials preceded each level. For the unary level, the participant was given two sounds via a simple matching analogy (A:B). The participant was asked whether the two sounds were the same or different. For the binary level, the participant was given four note patterns via a simple matching analogy (A:B::C:D) and asked whether the first pattern was exactly the same or different from the second pattern. For the ternary level, participants were given a six note pattern, in the form of a transitive inference task, and asked if the sound pattern followed a specific rule such as A is longer than B, B is longer than C, A needs to be longer than C to respond with a yes (A>B, B>C, therefore A>C). The quaternary level task was an extension of the ternary level task in that both dimensions (pitch and duration) were integrated into the one task with each dimension varying independently of one another.

An equal number of same and different trials were constructed for each level of relational complexity. There were eight trials (four same, four different) at the unary level, 16 trials at the binary level, 12 trials at the ternary level, and eight trials at the quaternary level. The unary, binary and ternary trials were equally split across pitch- and duration-varying patterns. Quaternary level trials involved both pitch and duration relations.

ISBN 3-931852-67-9
ISSN 1617-6847

Unary pitch trials consisted of two notes with an inter-onset interval (IOI) of 250ms. Total trial length was 850ms. IOI was adjusted in trials of increasing relational complexity to minimise the inevitable complexity-trial length confound. Duration varying trials contained the same number of notes and IOIs as those used for pitch trials at each level of relational complexity. Trial length differed according to whether trial pairs were same or different and the pattern of note durations used. Unary duration trials ranged from 850–1450ms. Binary duration trials ranged from 2250–2850ms. Ternary duration trials ranged from 3400–3700ms. Quaternary, like ternary, trials consisted of three groups of two notes but this time the relation involved the interaction of pitch and duration values. Total quaternary trial length was 3700ms.

2.3 Equipment

The experiment was run using the SuperLab v1.74 on an Apple iMac 266 MHz computer. A box for children to indicate their responses was constructed with buttons coloured green (for "same" responses), red (for "different" responses) and purple (for "I don't know" responses). Trials were randomised and individual items randomised to eliminate serial order effects.

2.4 Procedure

The task was introduced to individual child participants as a game that would get harder the more they played. The experimenter took time to ensure there was general understanding of the terms "same" and "different". For example, using cuisenaire rods as concrete tools, the child was asked to take any two rods from the box and explain any relationship such as whether they were different colours, the same length, the same shape. Following the child's example, the experimenter selected two different or same length rods and asked the child whether they were the same or different. This technique continued until the child and experimenter agreed on a response. After consensus was reached about the concepts same and different, the child was given a visual version of the auditory task that they were about to complete. Once the participant responded correctly an auditory practice trial of the same condition began. If there were no questions about the auditory practice trial, the test trials followed. This procedure was repeated at the beginning of each level of relational complexity for both pitch and duration patterns.

3. RESULTS

Accuracy was calculated using a discrimination index (DI) consisting of Hit Rate (HR) minus False Alarm Rate (FAR) and this index was used as the dependent variable in the analyses. The maximum accuracy score attainable was +1 and the minimum -1 (indicating that FAR exceeds HR). A score of zero reflects chance (equal HR and FAR).

The hypothesis stated that all age groups are able to complete unary and binary level tasks, that 8 and 11 year old children have mastery of ternary level tasks, and that 11 year old children have mastery of quaternary level tasks. As hypothesised, there was a significant linear trend of age and complexity, $F(1,83)=38.057$, $p=.000$. Figures 1 and 2 show the trend that accuracy is related to age and relational complexity of pitch and duration patterns, respectively.

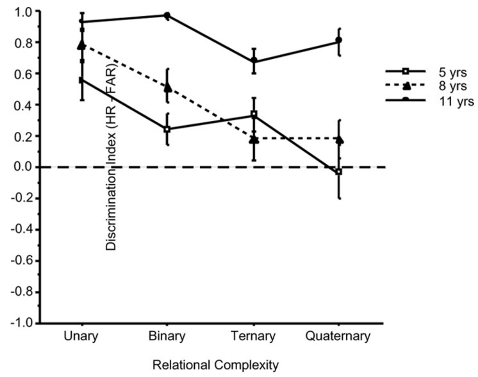

Figure 1: Mean discrimination index showing the interaction between relational complexity and age of participant for pitch-based patterns. Chance is zero – indicated by the horizontal dashed line. Error bars refer to standard error of the mean.

As hypothesized, all age groups responded significantly better than chance (zero) on unary pitch trials: 5 years, $t(26)=-4.51$, $p=.000$; 8 years, $t(27)=-8.34$, $p=.000$; 11 years, $t(30)=-20.86$, $p=.000$. On binary level pitch trials, the five-year old group also performed better than chance, $t(26)=-2.30$, $p=.03$, as did the eight-, $t(27)=-4.68$, $p=.000$, and eleven-year old groups, $t(30)=-43.15$, $p=.000$. On the ternary level pitch trials, the five-year old group again performed better than chance, $t(26)=-3.17$, $p=.004$, as did the eleven-year old group, $t(30)=-8.36$, $p=.000$. Surprisingly, eight-year olds did not perform better than chance on ternary pitch trials. As hypothesized, only the eleven-year old children performed quaternary level trials significantly better than chance, $t(30)=-9.40$, $p=.000$.

Accuracy on duration trials, shown in Figure 2, was generally poorer than in response to pitch varying patterns. The relationship between age and relational complexity can still be observed. The eight- and eleven-year old groups both performed significantly better than chance on unary duration trials, $t(27)=-3.81$, $p=.001$ and $t(30)=-11.18$, $p=.000$, respectively. At the binary level, only eleven-year olds performed the task accurately, $t(30)=-5.54$, $p=.000$. Again, only the eleven-year olds performed ternary duration trials at better than chance level, $t(30)=13.11$, $p=.000$.

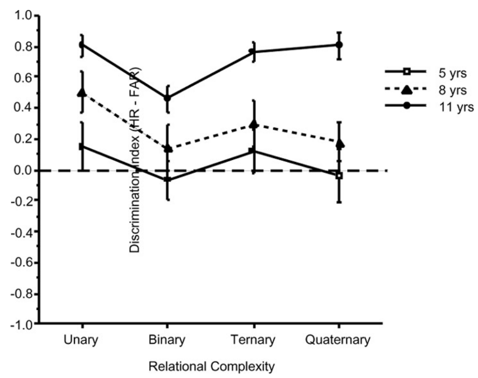

Figure 2: Mean discrimination index showing the interaction between relational complexity and age of participant for duration-based patterns. Chance is zero – indicated by the horizontal dashed line. Error bars refer to standard error of the mean.

ISBN 3-931852-67-9
ISSN 1617-6847

A general effect of age on overall performance was found. As age increased, accuracy on all tasks improved evidenced by a significant linear trend of discrimination index for age, $F(1,83)=47.393$, $p=.000$. Five-year old children were performing, overall, just above chance (mean DI =0.2). Eight-year old children recorded a mean discrimination index of 0.37 and 11-year old children recorded a mean discrimination index of 0.77.

4. DISCUSSION

The results provide support for Halford's metric of relational complexity in the auditory domain. Older children had the cognitive capacity to accurately perform problem solving tasks of greater relational complexity. More specifically, most children could complete unary and some binary level tasks, and 11-year olds were able to perform ternary and quaternary level tasks. An intriguing decrease in performance occurred for 8-year old children when presented with ternary level pitch tasks (see Figure 1). Their mean accuracy score dropped below that of the mean score for the five-year old children. It is possible that the eight-year olds were unable to segment the three components of the task and responded to the pattern as if it was binary. Alternatively, they were *just* able to segment the three components but did not yet have the capacity to process the three elements in parallel.

In this experiment, trial length increased with relational complexity. A second experiment has been conducted where binary tasks were extended in time so as to be the same length as ternary tasks. Performance on the extended binary tasks did not decrease to that of ternary tasks indicating that it is the relational complexity of the problem and not the temporal extent that underlies performance at different ages.

Children's accuracy scores suggest that solving tasks that consist of duration-based relations were more difficult than those consisting of pitch-based relations. There are two possible explanations for this finding. One is that the units of pitch and duration chosen for the task were not equivalent in JND terms although the pitch and duration units were based on established musical categories (consonant intervals and quarter, half- and whole-notes) that should be discernible. Alternatively, duration-based relations may implicate an additional step or relation because of the temporal dimension – our binary level duration tasks may be cognitively equivalent to ternary level pitch tasks.

Applied to musical development, Halford's (1993) theory proposes that understanding the different dimensions of music does not unfold as specific musical milestones at particular ages. Rather, dimensions of music are perceived and cognised to the extent that there is capacity available to segment and process the relations that comprise the event or pattern. Success will depend on the age and cognitive capacity of the listener. Musical development involves learning to decompose musical events into their constituent parts, group those parts or features that are closely correlated, redundant, or uninformative, and gradually increase the capacity to hold a number of relations in mind at any one time. The metric of relational complexity provides the means to measure and quantify task complexity and has implications for the way in which education may facilitate both performance and enjoyment of complex and capacity-challenging visual, auditory, spatial objects and events.

5. REFERENCES

1. Drake, C., Dowling, W. J., & Palmer, C. (1991). Accent structures on the reproduction of simple tunes by children and adult pianists. *Mus Perc, 8,* 315-34.

2. Halford, G. S. (1993). *Children's understanding: The development of mental models.* Hillsdale, NJ: Erlbaum.

3. Halford, G. S., & Wilson, W. H. (1980). A category theory approach to cognitive development. *Cognitive Psychology, 12,* 356-411.

4. Halford, G. S., Wilson, W. H., & Phillips, S. (1998). Processing capacity defined by relational complexity: Implications for comparative, developmental and cognitive psychology. *Behavioral and Brain Sciences, 21,* 803-864.

5. Handel, S. (1974). Perceiving melodic and rhythmic auditory patterns. *Journal of Experimental Psychology, 103,* 922-933.

6. Hargreaves, D. J. (1986). *The developmental psychology of music.* Cambridge: CUP.

7. Shuter-Dyson, R., & Gabriel, C. (1981). *The psychology of musical ability* (2nd ed.). London: Methuen.

ISBN 3-931852-67-9
ISSN 1617-6847