ACORNs: A tool for the visualisation and modelling of atypical development

Derek G. Moore

Rachel George

Institute for Research in Child Development,
School of Psychology,
University of East London.

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Correspondence should be sent to Derek Moore, Institute for Research in Child Development, Department of Psychology, University of East London, Water Lane, London E15 4NO. d.g.moore@uel.ac.uk; Tel: +44 208 223 4433

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Abstract

Across many academic disciplines visualisation and notation systems are used for modelling data and developing theory, but in child development visual models are not widely used; yet researchers and students of developmental difficulties may benefit from a visualisation and notation system which can clearly map developmental outcomes and trajectories, and convey hypothesised dynamic causal pathways. Such a system may help understanding of existing accounts and be a tool for developing new theories. We first present criteria that need to be met in order to provide fully nuanced visualisations of development, and discuss strengths and weaknesses of the visualisation system proposed by Morton (2004). Secondly we present a tool we have designed to give more precise accounts of development while also being accessible, intuitive, and visually appealing. We have called this ACORNS (An Accessible Cause-Outcome Representation and Notation System). This system provides a framework for clear mapping and modelling of developmental sequences, illustrating more precisely how functions change over time, how factors interact with the environment, and the absolute and relative nature of causal outcomes. We provide a new template, a set of rules for the appropriate use of boxes and arrows, and a set of visually accessible indicators that can be used to show more precisely relative rates, degrees and variance of functioning over different capacities at different time points. We have designed ACORNS to give a precise and clear visualisation of how development unfolds; allowing the representation of less ‘static’ and more transactional models of developmental difficulties (Sameroff & Chandler, 1975). We hope ACORNS will help students, clinicians and theoreticians across disciplines to better represent nuances of debates, and be a seed for the development of new theory.
Introduction

Notation systems are an essential part of many academic disciplines; aiding in the mapping of a problem space, the modelling of causal relations, and the development of theory\(^1\). Child development is a highly complex and data-rich field, yet the majority of published papers do not use visual representations to illustrate hypothesised developmental causal pathways; with theoretical accounts mostly given in written form. But, as Morton (2004) compellingly argued, the use of language alone to describe complex theoretical relationships between causes and outcomes can sometimes confuse rather than clarify accounts of theory, and even when these are accurate, it can be hard to keep in mind the whole picture when dealing with highly complex textual accounts.

Morton (2004) proposed that good visual models representing typical and atypical development could serve a critical function in helping to clarify ideas, providing a useful memory aid, and facilitating the representation of complexity in an easy to understand form. Visualisation of theoretical models of development can serve a key role in the formulation of theory by more clearly and explicitly representing different theoretical positions and by showing both common ground and incompatibility between them. Good visualisation tools may, therefore, play a useful and critical role in the formulation of more precise accounts of development and in the formulation of new, alternative ideas, revealing, perhaps, what we could know but don’t yet.

Of particular interest for students and researchers interested in developmental difficulties is the role that visual modelling can play in providing theoreticians and clinicians with a shared ‘conceptual space’ in which to outline assumptions and engage in more detailed interdisciplinary debates; helping, for example, to link theories dealing with gene action to those looking at social influences.

The creation of an effective visualisation tool, that can present comprehensive models of development, and describe effects across a wide range of factors and disciplines is not straightforward. The tool needs to remain ‘theory neutral’, affording a complete range of flexibility so that all possible theoretical proposals can be notated in a clear and concise way,\(^1\)

\(^{1}\) For example, chemistry now relies heavily on visual “ball and stick” depictions of molecules.
illustrating their subtleties and unique characteristics. A visualisation tool also needs to be intuitively and aesthetically appealing, easy to understand, and relatively easy to use. Clarity and ease of use are essential to allow good communication between disciplines, to help engage students in the complexity of the issues, and to facilitate public dissemination and understanding. Finally, a good tool should be able to produce models that are, in effect, ‘stand alone’ and able to depict development, without the need for detailed textual explanations.

Morton (2004) started this process by developing a notation system he called Developmental Causal Modelling (DCM). Here, we review DCM, highlight its strengths, build on these, and present a modified notation system we call ACORNS, that addresses some of the weaknesses of DCM. We believe this system has the potential to allow the creation of more comprehensive models that can give a better representation of some elements of the dynamic nature of ‘development itself’ (Karmiloff-Smith, 1998). First it may be useful to make clear the distinction between the terms plotting, mapping and modelling of development, which are sometimes used interchangeably but which need to be carefully defined, and are related but separable processes:

Plotting refers to the representation of developmental trajectories’ within single domains of functioning. This involve the creation of scatterplots and the fitting of regression lines to show how performance in a domain changes with age, and how it contrasts with typical development (see Thomas et al 2009). Information from plotting is essential to provide the detailed data needed to undertake wider and more detailed mapping and modelling.

In contrast we use the term Mapping to refer to a wider process in which functioning over many domains are represented in a time frame. Mapping may represent delayed, atypical and also relatively spared or typical outcomes for a population. It adds to plotting by allowing the direct contrast of outcomes across a full range of domains relevant for understanding the specific difficulties of a population. The idea is to give a full picture of the population

This approach highlights the importance of trying to develop tasks that can assess a capacity across individuals in phenotypes across as wide an age range as possible, so that the development of a particular capacity itself can be explored without this being confounded with differing task demands.
characteristics to show both the difficulties and specific characteristics of a population\(^3\), and also to show contrasts in typical and atypical aspects of functioning across populations, illustrating unique profiles of delay, sparing or difference. Mapping requires the identification of key points in development for many domains and the systematic placing of potential causes and outcomes into a time frame that can then inform subsequent modelling. Mapping may include the representation of known data as well as hypothetical causes and outcomes\(^4\).

*Modelling* is the process of representing hypothesized causal pathways between the functions and capacities that have been mapped, using arrows to indicate the direction of cause. A good visualisation and notation system can be used to map a condition, and then to model causal links. To facilitate clear, comprehensive and systematic mapping and modelling of the full range of developmental trajectories a notation needs to show not only temporal sequences, but also the different levels within which development occurs and the degree, rate and variance of outcomes in functioning achieved over different points in time. We deal with this further below.

In considering systems for the visualisation of developmental difficulties we began by identifying six criteria that need to be achieved by a notation tool in order to be able to fully model child development. Specifically, we concluded that a notation system needs to:

1) provide a structured, comprehensive conceptual ‘frame’ in which development can be shown to occur;

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\(^3\) Morton (2004) proposed that mapping should be restricted only to those outcomes that are critical in defining a specific developmental difficulty or syndrome, and that for parsimony one should avoid ‘redundant’ pathways that show non-specific ‘general’ delays, concentrating on showing outcomes that are unique. We contend that to gain insight it is not always just a matter of mapping those behaviours that define a syndrome but also those that appear relatively spared or show contrasts with other populations.

\(^4\) Of course mapping can never complete because research data is always expanding. Indeed one of the main activities of experimental developmental psychology is to create new experimental tasks that elicit behaviour to reveal even more subtle differences between populations; and the creation of tasks that can be used to plot developmental trajectories over wider age ranges promises to produce more detailed developmental data that can then be mapped.
2) allow the full mapping of functions at appropriate levels within the frame;

3) clearly and unambiguously illustrate links between causes and outcomes within and across levels;

4) represent the temporal order of developmental sequences;

5) facilitate the clear representation of transactional, bi-directional processes over time;

6) Indicate how rate of development, degree of functioning and variance of performance in capacities may have changed over time and indicate how these compare with what would be expected for chronological age (CA) and developmental age (DA).

**Overview of Developmental Causal Modelling (DCM)**

Morton (2004) started with the conceptual ‘frame’ illustrated in Figure 1. The frame imposed a new structure to modelling by requiring users to map causes and outcomes into one of the three levels of explanation: biological, cognitive or behavioural; or as an environmental factor. This can help in providing more integrated accounts of development (see Oliver and Woodcock, 2008). The three main levels are depicted on a page separated by horizontal lines. Once specific capacities are mapped, these can then be linked by arrows to create a causal model. Separating causal elements into these three main levels challenges theoreticians to provide accounts that begin with a genetic and biological cause at the top of the page and then proceed down the page via hypothesised cognitive structures to observed behaviours, using arrows to show the causal direction of influence. Environmental factors are placed to the side in an area separated by a vertical line with effects depicted by arrows coming from the side and acting on factors in the other levels.

[Figure 1 here]

DCM has been used by Morton in collaboration with other researchers to model disorders such as dyslexia (Morton & Frith, 1993, 1995, 2002), psychopathy (Blair, 1995), conduct disorder (Krol, Morton, & de Bruyn, 2004), developmental coordination disorder (Sims & Morton, 1998) and more recently panic disorders (Fava & Morton, 2009). Figure 2 gives an example of how Morton (2004) used DCM to represent three theories of autism (see also Frith, Morton, & Leslie, 1991).
The strength of DCM is in the way the notation clearly shows different levels of explanation and, as illustrated in Figure 2, can be used to illustrate differences in causal links made by contrasting theories. Separating factors into levels is clearly a useful and meaningful approach and introduces important discipline into the creation of models of developmental difficulties. However, to date the DCM approach has not been widely adopted, notwithstanding the papers outlined above. One reason for this may be that DCM is perhaps not yet sufficiently flexible to create fully developmental models and requires further modifications to be able to fully meet the criteria we outlined. In particular DCM may require changes to better deal with ‘transactional’ elements of development.

Transactional accounts (Sameroff & Chandler, 1975; Sameroff, 2009) are fundamental to many theories; and describe bi-directional processes in which the individual and the environment mutually affect each other over time while capacities are themselves also changing. These processes, for example, are implicit in Hobson’s social-affective theory of autism (Hobson, 1993, 2002) in which primary differences in social-affective engagement in children with autism are hypothesised to lead to a differing sense of the nature of shared meaning in interaction with others, which can then lead to differences in identification and a sense of self in the individual, impacting further on the development of meta-cognitive and mentalising processes.

Such an account, whether or not one agrees with it, requires the representation of bi-directional relationships over time between the individual and their social environment. These were not represented in the DCM model of Morton reproduced in Figure 2 (c). More importantly, although it might be possible with DCM to construct a model using double ended arrows going to and from the environment, DCM is not set up to convey how bi-directional relationships themselves can change over developmental time.

Note that the depiction of different cognitive and behavioral levels corresponds with the ideas of representing endophenotypes (Gottesman & Gould, 2003): underlying cognitive or behavioural processes that have genetic origins. But note that DCM and ACORNS are ‘theory neutral’ and allow the mapping of all ‘cognitive level’ and behavioural process that may be critical for defining the phenotype, whether or not they have been hypothesised to be genetic in origin.
To deal with this issue requires the extension of DCM and the addition of an explicit time dimension; along with a re-evaluation of the way the environment is represented spatially with respect to the other levels. Placing the environment to the side of the other levels, as DCM does, means it is not possible to easily show how biological, cognitive and behavioural factors influence the environment and visa-versa over time. Inadvertently perhaps, environmental factors appear to be given less significance and appear more distal than other factors in other levels, potentially biasing theoreticians towards a depiction of development in which the environment acts upon other levels but is not itself changed. As currently formulated DCM may restrict the systematic representation of transactional processes and perhaps is not as ‘theory neutral’ as Morton hoped. The ability to represent bi-directional processes involving unfolding interactions between the individual and their environment is essential for depicting many theories, not only those that deal with social-affective development, but also those dealing with gene-environment interactions 6.

With respect to our six criteria for visualisation we therefore conclude that: 1’) DCM provides a very useful initial conceptual frame for mapping how development occurs, but might usefully be revised to better allow representations of bi-directional individual-environmental influences over time; 2) DCM provides an excellent and useful level of discipline for the placement of capacities and boxes in levels, but that this may be improved by changes to the number of levels and the addition of a time dimension; 3) while DCM adds important discipline to modelling by making it necessary to give a causal explanation that moves from the biological to the behavioural using arrows, there is perhaps even more that could be achieved by adding further discipline on the use of arrows ; 4) correspondingly, DCM as it stands is difficult to use to present the temporal sequences and relationships between cause and outcome behaviour, and perhaps needs modifying so that capacities can be better shown to be changing over time; and 5) DCM notation tends to favour uni-directional models leading from the biological to behavioural, which may limit the depiction of transactional environmental effects; finally, 6) DCM does not provide a way, except through

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6 Gene expression is not simply determined by the structure of DNA, but by bi-directional processes such as methylation, which change the amount of activity of DNA sites, and by differences in the way DNA interacts with histones. Each of these ‘epigenetic’ processes (Gotlieb, 2007) influences the activation or silencing of genes. A modeling system needs to be able to clearly represent how these processes progress over time.
the use of text, of representing the relative size, rate and variance of outcomes across different capacities and over time.

In summary while DCM gives a very useful foundation with which to begin modelling, to create more comprehensive, elegant and precise models that represent a truly developmental picture, significant modifications may be required. Similar concerns were also raised by Thomas (2005). It is for this reason that we have developed ACORNS: an Accessible Cause-to-Outcome Representation and Notation System

**An Accessible Cause-to-Outcome Representation and Notation System**

In developing this new tool we are conscious that visual models can easily misrepresent the nature of development. Karmiloff-Smith (2009) has warned against what she terms “boxology”, in which atemporal box-and-arrow models from adult neuroscience are uncritically and unthinkingly extrapolated to infancy (see Karmiloff-Smith, 1997; Pennington, 2009). Any notation must be careful that it does not imply that infant and child capacities depicted in boxes are somehow ‘fixed’, but that in fact these are undergoing change over time. For this reason we have devised ACORNS to allow the depiction of capacities changing and interacting over time.

Our own work is focussed on understanding fundamental cognitive, social and language processes in atypical populations from infancy to adolescence (e.g. Dockrell et al., 2001; Dockrell et al., 2003; Moore et al., 2007; Moore et al., 2008; Parron et al., 2008; Hubert et al., 2007); alongside work exploring direct and indirect influences of social and physical environmental factors on the development of typical and at-risk populations (e.g. Moore, 2001; Moore et al., 2003; Moore et al., 2010; Moore et al., 2011; Wall et al, 2009). Consequently we have become aware of a need to construct better ways to visualise development in all its complexity. As a step on the way to the full ACORNS notation outlined below, for a review paper with Katie Cebula and Jennifer Wishart (Cebula et al.,

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7 While in the adult brain there is evidence for localization and specialization of function, this does not reflect the starting state of the infant brain which has high initial plasticity only becoming specialized and localised as it comes to selectively ‘filter’ inputs over time (Huttenlocher and de Courten, 1987; Huttenlocher and Dabholkar, 1997; Johnson, 2001; Neville et al, 2006).
we adapted DCM to illustrate a transactional model of early social and cognitive development in infants with Down’s syndrome (DS); see Figure 3.

What Figure 3 depicts is a hypothesised causal model, based on existing data, which illustrates how, in babies with DS, early attention difficulties at the cognitive level might lead to differences in social behaviour; which in turn lead to differences in maternal behaviour; which may then in turn lead to additional effects on social and cognitive development for the infant (see Moore et al, 2002; 2008). Irrespective of the validity of this theoretical account, the model illustrates four initial modifications we made to DCM:

Firstly, we added a horizontal time dimension that allows the mapping of capacities over time moving from left to right across the page; secondly we represented the environment not as separate and to the side, but as equivalent to the biological, cognitive and behavioural levels, placing it along the bottom of the page; thirdly, for ease of visualisation, we changed the depiction of boxes to make it appear as though levels were occupying three-dimensional space; fourthly, we imposed some initial spatial constraints on the orientations of arrows. We subsequently identified and added further modifications and changes to create the ACORNS system which we explain in more detail below.

**Adding time**

The full ACORNS frame is depicted in Figure 4. The addition of a time axis allows the representation of effects not just at one fixed point in time, but in a sequence over critical points in time, as defined by the theory depicted. These may be points along linear or non linear trajectories indicated when plotting development in each single domain (see Thomas et al, 2009). A key strength of the notation is that the time dimension allows models to be extended over as many pages as necessary to depict the ongoing nature of development in the

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8 The basic framework, the hypothetical models outlined in this paper, notational components and draft templates for creating models are available on line at www.uel.ac.uk/IRCD/ACORNS.htm. Templates have been created with Microsoft Word in Windows 7 and contain all the symbols required, so users can simply cut and paste elements to create their own models.
same way as a musical score. The depiction of changing influences over time is also aided by modifications to the levels and by a more disciplined use of arrows outlined below.

[Figure 4 here]

Re-aligning levels
In the ACORNS frame we add both a physical and a social environmental level, one above and one below the three levels initially outlined by Morton (2004). This is important, for showing the hypothetical way that the environment can act upon the individual either through direct physical and biological processes such as the impact of recreational drugs in utero (e.g. Moore et al 2010; 2011); or through the impact of social processes such as parenting, peer interactions, schooling and community influences (e.g. Wall et al, 2009).

Further, Morton recognized that it may make sense to allow the further split of the ‘cognitive’ level to better differentiate cognitive and social-affective factors. Thus we depict these two sub-levels as separated by a dashed line to reflect the fact that some factors link across the interface of cognitive and social-affective levels. We also suggest that where necessary one could add conative and motor sub-levels.

Improving visualisation of levels
With ACORNS we also wish to improve visualisation and give the sense that levels exist as separate planes in three dimensions. To create this effect we suggest using diamonds instead of square boxes. This visualisation allows clearer distinctions between boxes in levels, helping to differentiate between causal developmental processes that are occurring within a level, versus those that occur across levels. This is also aided by the more disciplined use of different arrows within and between levels.

Using vertical and diagonal arrows to eliminate conceptual shortcuts
To better differentiate between causal pathways acting within and between levels we propose greater discipline in the use of orientations of arrows: restricting arrows that make links across levels to vertical and arrows that link factors within levels to a diagonal orientation.

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9 Similarly there would be a case for depicting sublevels for any level when detailed debates are being illustrated
When one factor has been found to have a statistical relationship with a different factor at a different level at a later point in development it is tempting to simply connect these two points. The restriction on the use of arrows, in addition to improving the visualisation of within- and between-level influences, prevents theoreticians inadvertently bypassing developmental pathways by simply drawing an arrow linking two factors over time without either giving an account of the potential intermediate causal relationships, or specifying the point in time when the effect begins to take place. In arrow and box diagrams of development these forward linking ‘conceptual shortcuts’ are commonplace, but are potentially a dead-end in terms of understanding development. Restricting arrows in the way we propose challenges theoreticians to either provide a full and explicit account of a hypothesized chain of mediating and moderating factors across and within levels, to fill in the full causal chain, or to say why no intermediate processes are needed; but nevertheless to have to commit to a hypothesis about when the first factor began to affect the other in time.

Using horizontal arrows to link changing capacities within domains over time
In order clearly illustrate change within domains of functioning over time another convention on the use of arrows is required. In ACORNS, horizontal arrows are only used for linking together common elements of functioning in a domain over time, with the linked boxes representing the state of functioning in that domain at the different time points. This is then supplemented by the addition of indicators that show the differing degrees, rates and variance of functioning in that domain at the points in time. These are described in detail shortly.

Figure 5 shows how these modifications and conventions can be applied. The hypothetical model illustrated shows a developmental ‘chain’ in which behaviour influences the social environment which in turn has reciprocal effects on behaviour leading to effects on cognitive and biological levels. This is a relatively simple model with a direct link from a genetic cause to brain and cognitive outcomes, showing the temporal sequence and the subsequent transactional influences. Real development is likely to far more complex and genetic processes also require transactional representations.

[Figure 5 here]
Using indicators to notate development

The ACORNS visualisation depicted in Figure 5 illustrates how adding a time dimension and changing the representation of the environment helps to overcome some of the difficulties that DCM has in meeting the six criteria for visualisation we outlined in the introduction: allowing clearer depictions of transactional processes over time and across levels. However these changes alone do not allow the clear representation of all parameters that are needed to illustrate the dynamic nature of development. Specifically, this model does not represent the differing degrees of functioning at each point in time across capacities, nor the rate with which that degree of functioning was attained, nor population variance in functioning; nor do these yet allow one to represent and compare functioning from one time point to another.

Furthermore, when giving an account of developmental difficulties, it is not just a case of presenting the ‘raw’ degree, rate or variance in functioning, but also of considering the relative extent of delays or differences compared to what would be expected for typical children of a particular chronological age (CA) and/or developmental age (DA); perhaps identifying specific differences or delays relative to the general levels achieved by that population at a point in time or revealing areas of functioning that are relatively spared compared to the general developmental level (DA).

Currently when researchers present models, for example in the DCM models and our own in Figures 2 & 3, there is no clear way of visualising these parameters. Rather there is always a need to supplement the visual element of models with large amounts of text, which are entered in the boxes themselves or is added to the figure legend. Even with the modifications to DCM we illustrated in Figure 3, it was necessary to use text in order to explain the subtleties of developmental outcomes, for example adding terms such as sparing, weakness, dysfunction, or difficulty alongside the name of the capacity concerned.

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10 Note that throughout ACORNS we use the term degree of functioning rather than level of functioning in order not to confuse this level with that of behavioural versus cognitive levels etc.

11 Note we use the term developmental age, rather than mental age, as this comparison may apply at any level of functioning not just the cognitive level.
The fact that there is a need to add complex terminology within boxes, or as an extended and complex legend, implies that current visualisation tools are not yet sufficiently nuanced to depict key and critical parameters of development and create ‘stand alone’ depictions of models.

To overcome this limitation we propose three additional ACORNS indicators that are intuitive and easy to read and can add clarity to basic box and arrow models. These three indicators show relative degrees, rates and variance, and can be placed with boxes at different points of emergence of a function to indicate differential rates across different functions over time. These additions will allow theoreticians not only to be explicit about ‘causal assumptions’ but also to be explicit and more precise about their ‘outcome assumptions’ and give a clear and accessible representation of the unfolding dynamic nature of development. Figure 6 shows these three indicators.

[Figure 6 here]

*Rate of achievement of functioning:* the first indicator is a simplified clock face used to indicate different rates of development from advanced to delayed. There are six ordinal settings where the clock points to early, on time or ever later points on the dial and is more shaded the more delayed development is relative, first to CA, and then to DA. The use of shading in these indicators is a further aid to visualisation, so that when elements are viewed as part of a complex model it is easier to get a sense of the whole picture. The six settings are:

i. A white clock face set at “five-to”; indicating an advanced or early rate relative to chronological age (CA).

ii. A white clock face set at noon; indicating a typical rate of development.

iii. A grey clock face showing “five-past”; indicating a delay relative to CA but relatively advanced compared to general developmental age (DA);

iv. a grey clock face showing “quarter-past”; indicating a delay equivalent to general DA

v. a dark grey clock face showing “twenty-past”; indicating a relative delay compared to DA;
vi. a black clock face with crossed hands indicating no development.

Degree of functioning: The second indicator is a vertical cylinder used to depict six possible degrees of functioning. Here the “liquid” in the cylinder is full and clear to indicate typical functioning and fills up with ever darker liquid to show decreasing degrees of functioning relative to CA and DA. The six settings are:

i. a white cylinder with an additional white ring on top indicating a precocious or heightened degree of functioning relative to CA\textsuperscript{12};

ii. A ‘full’ white cylinder indicating a degree of functioning that is typical;

iii. a half-and-half, white and-grey cylinder indicating a degree of functioning that is less than expected for CA but relatively spared compared to DA;

iv. a simple all grey cylinder to indicating a degree of functioning that is DA-equivalent i.e. that which would be expected for DA;

v. a half-and-half, grey-and-black cylinder indicating a degree of functioning that is relatively impaired compared to DA;

vi. finally an all-black cylinder indicating a deficit or absence of an ability.

Variance in functioning: Although less often included in accounts of development; in a number of cases differences in variation of functioning are a critical element for understanding outcomes. We propose using a double arrowed box with a central line to represent the full possible range of variance, with typical variance indicated by a half-filled box around the central line, reduced variance by a reduced spread; variance greater than normal by a fully grey box and no variance by an empty white box. In the models below we have not always included this third indicator for the sake of brevity, but these may be

\textsuperscript{12} Note that while a heightened degree of functioning could be positive for typical children it may be an important indicator of difference in atypical populations, such as calendrical calculation in Autism, or the over-expression of Hsa21 genes in Down’s syndrome.
important for presenting a full picture of outcomes. See for example greater variance in performance in children with DS (Wishart, 1993)

In figure 7 we show the three indicators linked with boxes to give a clear visualisation of six of the most common combinations of outcomes, from a precocious ability through to a deficit. It is important to note that this is not all the possible combinations. A key reason for having three indicators is that they allow the independent depiction of three aspects to development and allow them to be combined in many ways to depict different outcomes. Simply using a single indicator to depict delay would not be sufficient\textsuperscript{13}.

[Figure 7 here]

Combining visualisation and notation

A hypothetical model using the proposed ACORNS visualisation conventions along with the ACORNS indicators is presented in Figure 8.

[Figure 8 here]

The hypothetical model represents a chain of development and indicates outcome assumptions using indicators. The model shows how an over-expression of a physical environmental cause (Env1, perhaps a drug) that might lead to a delay in the expression of a hypothetical Gene (Gen2). This is alongside the normal expression of another gene (Gen1) which is unaffected. The model then shows the chains along which Gen1 & Gen2 affect cellular processes (Bio1 & Bio2) and lead to changes in brain structure or function (Brn1 & Brn2). The preserved functioning of Brn1 leads to typical outcomes for affective functioning (Aff1) and leads to typical behaviour (Beh1) at this point in development. This is accompanied by typical early social environment (Sen1). Meanwhile delays in Brn2 lead directly to delays in Cog1. In this model this then leads at a second point in time to an early emergence of a behaviour (Beh2 e.g. such as aggression). This in turn then begins to affect

\textsuperscript{13}While, for example, a general DA-equivalent delay in rate of development may commonly lead to DA-equivalent performance, as depicted in figure 7, box D, this is not always what occurs. While some abilities may be delayed in emergence, the final degree of performance may be typical or even precocious; for example, language production in bi-lingual children.
the social environment leading to a delay in Sen2 (for example, a reduction in maternal sensitivity). This then combines in a transactional process with Beh2 to lead to a specific impairment at a third point in time (via Sen3) in Beh3 (perhaps in something like cooperative behaviours), which in turn affect cognitive behaviour (Cog2) and affective reactivity (Aff2) which in turn leads to a change in a biological process, such as an increase in cortisol (Bio3), as a consequence of heightened stress reactivity. This in turn may then affect the timing of the expression of other genes (Gen3) and lead to a secondary biological effect (via Bio3 & Brn3), and so on.

We do not claim that this model actually reflects a real pattern of development, but rather is used to illustrate to represent the causal chain outlined in the two paragraphs above; and how the passage of text can be far more clearly conveyed and is easier to understand and conceptualise when accompanied by a clear graphical notation that can stand alone from the text and accurately and concisely depict cause and outcome assumptions.

With ACORNS notation it is possible, more clearly and directly, to see where predictions are being made with respect to increased or decreased degrees or rates of development in different levels and domains; and to see how this might change over the course of different points in time. And more critically it is easier to see where there are flaws in a model and where there are gaps.

Finally, to give a real example, Figure 9 re-draws the model of early social development of infants with DS we outlined in Figure 3 using the ACORNS notation based on Cebula et al, (2010); (also see Fidler 2005; Fidler et al 2008). In Figure 9 we use the ACORNS conventions to better express outcomes and re-present hypothesised pathways from infancy to childhood. We show in more clarity the hypothesised paths by which specific deficits in brain systems (ocular control, Ocul; and posterior systems, PosAtt) might lead to specific differences in attention to dynamic stimuli (Dynatt) and in general attention regulation (GenAtt); and on through to later social environmental transactional processes.

The model shows how these initial factors might cause differences in looking to objects (Lkobj); and correspondingly lead to a compensatory change in the social environment, with mothers showing increased warmth (Mwar). Correspondingly this might lead in the infants to increased attention to mothers (LkM) and to people in general (Lkpeop), which is also
determined by relatively spared propensities to engage with others (Engage), which reflect relatively spared elements of the social brain (SocBrai).

This spared level of engagement is also hypothesised to be the cause of over imitation (Imitat) and a relatively spared capacity to engage in joint attention (JACap). However the model shows how the tendency to focus on the mother might lead to a further change in these infants’ environment with mothers taking a more directive role in interactions (MDir). In turn this model indicates how this environmental change combines with a tendency to over-imitate and leads to a reduced propensity to initiate joint attention (JAinit), which may be compounded by differences in frontal functioning (Frontal) which lead to differences in executive functioning (ExFunc) which impact on planning of joint attention, even though the basic capacity may be relatively intact (JAcap).

This can then lead to a further difference in social environment in which mothers show a reduced tendency to wait for infants to make topic bids (Mtopi), which when linked with a reduced propensity to initiate joint attention might lead to reduced propensity to initiate requests with mothers (ReqP) which also leads to greater variation in sense of agency (Agency) that may impact by also increasing variation in Theory of Mind within the DS population (Tom). The model also shows how the ongoing impact of maternal directiveness might reduce mothers’ propensity to use expressive language and cognitive terms in conversations (MExp) leading to reduced attention to emotional stimuli (AttEm) and to poorer emotion recognition (EmRec) also impacting on later Theory of Mind.

Again, we hope the visual model depicted makes it easier to get a fuller sense of the hypothetical causal picture, which has taken many dense sentences to describe in the preceding paragraphs. By re-describing this model into ACORNS we can visualise and describe more clearly hypothesised patterns of spared, delayed, or specifically impaired areas of functioning for an atypical population; and reveal areas where the model may need to be better defined.

**Conclusion**

This paper has given the argument for the use of visual models to provide clarity, rigour and ease of understanding, and to facilitate the understanding and development of theories of developmental difficulties across disciplines. We reviewed DCM and identified a set of
additions and modifications to create a more comprehensive notation system we have called ACORNS which can potentially facilitate clearer modelling of the dynamic nature of ‘development itself’ (Karmiloff-Smith, 1998). Building on the solid foundations laid by Morton (2004), this notation has been designed to meet the six criteria outlined in the introduction and be both visually appealing and detailed and specific. We look forward to feedback on how successful and useful this proves to be.

The notation allows the representation of a full range of cause and outcome models including bi-directional effects of individuals and their environment. It also allows the representation of differential effects of development across any range of time span, and allows the representation of rates, degrees and variance in outcomes, and thereby can reflect the all important nuances of developmental difficulties. The notation also imposes constraints on the use of arrows in order to make it clear when an assumption is being made or missed with respect to development. ACORNS therefore adds to DCM by providing a more nuanced account of developmental difficulties that challenges theoreticians to fill in missing links and avoid overly simple accounts, whether biological or social in origin.

We hope ACORNS will help students and researchers across disciplines work together to move beyond limited areas of expertise and begin to grow some “theoretical oak trees”. The aim has been to create a notation that can facilitate a better understanding of the complexities that underpin the development of developmental difficulties. The mapping and modelling we have presented in this paper have been hypothetical or restricted to a limited aspect of development, and have been necessarily incomplete. However the ACORNS notation may make it possible to link different elements of developmental accounts from different research groups and across fields. Our future aim is to build a shared understanding of what can and should be mapped, what elements are missing, and facilitate clear and detailed debates about causal assumptions.

It would be inappropriate for us to have tried to map and model outside of our area of expertise, but we hope ACORNS can help create full mappings and models across phenotypes and facilitate better coordination, collaboration and synthesis from biological, behavioural and social sciences. We hope people from different fields, from genetics to sociology, will see the worth in trying to use a common notation system to fit together their different accounts of development into a broader developmental jigsaw. Most importantly a
more detailed and common system will allow clear comparisons to be made between phenotypes in the sequence and effects of factors.

In addition to making better sense of available data to create models, there is a clear need for more detailed studies of developmental trajectories, showing the changing nature of capacities across developmental ages; and also a need for longitudinal studies that can test hypothesised causal relationships between time points within individuals. Indeed we may not yet be in a position to fully map and model many aspects of development for many phenotypes, and acquiring the detailed level of data that will facilitate detailed mapping however will require significant investment in time and money. However, in the meantime ACORNS can serve a useful function in mapping out missing areas, unpacking causal assumptions and revealing what we do not yet know and need to find out.

As with DCM this approach can be used not only to depict the development of populations, but also has applications for mapping outcomes for specific individuals and serve as a useful clinical tool. We hope, therefore that, this approach can also have day-to-day utility for clinical practice allowing clinicians to map out and better understand the unique developmental profiles of individuals with difficulties.

The ACORNS diagrams depicted show it is possible to depict dynamic aspects of development with box and arrow diagrams while overcoming some of the inherent dangers of ‘boxology’ (Karmiloff-Smith, in press). Whereas DCM presents a relatively fixed picture of development, ACORNS shows a sequence of linked developmental events over critical points in time and, with the use of the indicators, can show change and relative functioning over time.

There are still of course limitations with this approach in visualising the fully dynamic nature of development. In future we will be developing more sophisticated software that can be used to give more detailed animated visualisations of development; allowing users to scroll, stretch and ‘zoom’ over time in a fine-grained way (see for example, Rosling, 2007). This will allows us to depict the rapidly changing patterns of interactive specialization (Johnson, 2001; Karmiloff-Smith, in press; Mills et al, 1997) that occur from infancy, through childhood and fill in the intervening periods between the time points depicted by ACORNS allowing far better models of developmental disorders (see Karmiloff-Smith, 2009).
There will still, however, be a need for notation tools that can depict nuanced models on typescript pages for publication, and for generally accessible tools for sketching out ideas which ACORNS can be used for. We hope that people will see the benefits of this approach for this purpose and will use ACORNS to develop clearer and more developmental theoretical accounts. We would encourage users to post their models on the ACORNS website so we can share in an endeavour to better map and model developmental difficulties and have open and detailed debates.
References


Huttenlocher, P. R., & Dabholkar, A. S. (1997). Regional differences in synaptogenesis in


Figure 1: Morton’s DCM frame

- Environmental factors
- Genetic factors
  - Brain conditions
  - Cognitive factors
    - Behavioural descriptions
Figure 2: Three models of autism outlined by Morton using DCM (2004; pages 91, 117 & 132)

a) central coherence

b) executive function

c) affective deficit
Figure 3: Modified DCM to present a model of early social and cognitive development for infants with DS; from Cebula, Moore & Wishart (2010)
Figure 4: The full ACORNS frame

Physical Environment

Biology

Affect

Cognition

Behaviour

Social Environment
Figure 5: Using ACORNS to depict a hypothetical model showing cause-outcomes acting bi-directionally across levels over time.
Figure 6: ACORNS indicators of rate of emergence of a function, degree of functioning, and amount of variance

<table>
<thead>
<tr>
<th>Rate</th>
<th>Degree</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced</td>
<td>Heightened</td>
<td>Typical</td>
</tr>
<tr>
<td>Typical</td>
<td>Typical</td>
<td>Increased</td>
</tr>
<tr>
<td>Relatively advanced</td>
<td>Relatively spared</td>
<td>Reduced</td>
</tr>
<tr>
<td>DA-equivalent delay</td>
<td>DA-equivalent</td>
<td>None</td>
</tr>
<tr>
<td>Relatively delayed</td>
<td>Relatively impaired</td>
<td></td>
</tr>
<tr>
<td>No development</td>
<td>Absent</td>
<td></td>
</tr>
</tbody>
</table>

Typical: typical, Increased: increased, Reduced: reduced, None: none.
Figure 7: Combining indicators with boxes to show six common developmental outcomes

- **A**: Advanced and Heightened
  - Advanced rate and heightened degree compared to typical; typical variance

- **B**: Typical development
  - Typical rate of emergence; typical degree attained; typical variance

- **C**: Relatively advanced and spared
  - Relatively advanced emergence versus DA; relatively high degree v DA; greater variance

- **D**: General delay and impairment
  - Rate and degree less than CA, as expected for DA; possibly with similar variance

- **E**: Relatively delayed and impaired
  - Slower emergence than other DA comparable abilities and reduced degree v DA; often greater variance

- **F**: Absolute deficit
  - No emergence; no measurable degree; universal hence no variance
Figure 8: A hypothetical developmental model using the complete ACORNS frame and indicators, showing changes in degree and rate of functioning.
Figure 9: Using ACORNS to re-map and model real data presented in Figure 3 showing early social development in infants with DS (based on Cebula et al 2010).