An empirical and computational study of variability in individual differences and cognitive development

Thesis Proposal

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Overview

In this proposal I set out a study to examine the relationship between two forms of cognitive variability. These are cognitive development and individual differences. Cognitive development refers to the general increase in reasoning ability that individuals show over time. Individual differences refers to the way individuals of similar ages differ on intellectual tasks. Although these may be separable forms of cognitive behaviour, theoretical accounts of the mechanisms that influence their variability show a degree of overlap. This points to the possibility that differences within these behaviours may be represented by differences along a single dimension. I propose to investigate this, using empirical and computational methods.

To understand the nature of this relationship, this proposal details an empirical study in which children of different actual ages are ability matched and their performance compared on a range of cognitive tasks. By assessing the cognitive profiles of two groups matched on mental ability, this research aims to establish whether differences are qualitative or quantitative in kind. If younger and older children of equal mental age show qualitatively different profiles of performance across a range of cognitive tests this would suggest differences in cognitive development and intelligence represent differences on separate cognitive dimensions. However, if these children show quantitatively similar profiles on cognitive tests this would suggest that variability in cognitive development and intelligence may be represented as differences along a single dimension.

This proposal then outlines a programme of computational modelling aimed to further clarify the relationship between these forms of variability. This entails systematic manipulations to a set of existing computational models. Each set of manipulations seeks to evaluate the role of mechanisms that are assumed to underlie variability within both domains. These models, all of one particular class, called connectionist networks are learning systems that share commonalities with real, neural information processes. That is, they include a range of parameters that may be taken to resemble biological properties
in the brain. As such they provide a basis for exploring candidate mechanisms of
cognition and development. By altering the properties that influence their learning it is
possible to affect performance in one direction or another (e.g., more, or less intelligent
behaviours).

Introduction

People of the same age differ with respect to their performance on cognitive tasks. The
individual differences approach to the study of intelligence has sought to *describe* these
differences. This involves assessing an individual’s performance on intellectual tasks by
comparing their scores to the norm for a given age. This quantitative focus on *within-age*
differences was first established by Binet and Simon (1911), as a means of identifying
children in need of special education. It allows one to evaluate, for example, whether the
performance of a 10 year old is within the normal range given the performance of most
10 year olds. Similarly, it allows one to establish whether an individual’s performance is
above or below average for their age group. The ability to delineate the range of
performance expected in different age groups, gave rise to the notion of *mental age*
(MA). From this followed the concept of the *intelligence quotient* (IQ) – an index of ones
mental ability given their actual, or chronological age (CA). This is expressed as: \( IQ = \frac{MA}{CA} \times 100 \). The fact that performance on different cognitive tasks is usually found to
correlate positively and that a single latent variable can be extracted using factor analysis,
has led some to conclude that a general factor (\( g \)) underlies differences in intelligence
(see e.g., Bartholomew, 2004).

Cognitive development refers to the increase over time in a person’s ability to
reason. In contrast to the individual differences approach, the goal of this approach has
been to *explain* how intelligence develops. The primary focus has been to understand
what accounts for *between-age* differences in reasoning, or mental ability as one grows
older. Piaget’s framework of cognitive development (1971) typifies this qualitative
approach in which representations of increasing complexity are developed through interaction with the world and maturation. Mental age is an important concept to theorists within this approach, as it provides a framework for establishing the forms of thinking that an individual is generally capable of, at a given age.

These two approaches to the study of intelligence have historically taken different paths (see e.g., Davis and Anderson, 1999) and experimental data supports this divergence. Kane and Brand (2006) assert that cognitive development and differences in general intelligence have little in common. They state, “that as children mature, their cognitive abilities become increasingly differentiated, irrespective of individual differences in general ability” (p.44). Other work presented in a review by Spitz (1982) further supports the notion that these two forms of cognitive variability are qualitatively different. For example, in his review of Merrill’s data (1924) Spitz outlines findings in which younger and older children are matched on mental age (mean MA of 8) and their performance then compared on the range of sub tasks from the Stanford-Binet intelligence test (Terman, 1916). Significant differences are reported between younger children (mean CA of 5:6) and older children (mean CA of 11:9). These differences are represented in Figure 1 below.
The finding that younger children perform better on tasks involving verbal reasoning whilst older children perform better on tasks tapping maturation and experience supports the view that qualitative differences underlie variation in these behaviours. That is, cognitive development and differences in general intelligence may represent differences along separate dimensions.

Spitz’s approach to the question of dimensionality is straightforward: Match two groups on mental age and observe which tests the older, less able children show the largest MA lag, and which tests the younger more able children show the greatest MA acceleration. However, Spitz’s comparisons of “extreme groups” may have introduced possible confounding factors. In Merrill’s study, the mean IQ of the younger group was
While atypical development is a valid form of cognitive variability, debate exists as to whether performance in atypical populations and performance within the normal range can be placed on the same dimension (see e.g., Thomas, Karmiloff-Smith, 2003). To reduce the chances of introducing such confounds, this proposal focuses on comparing children within the normal range. There has been little work done comparing the relationship of cognitive development and individual differences in these populations. Consequently it is not clear whether younger more-able, and older less-able children of equal mental age and within the normal range would show the same kinds of dissociations on intelligence tests as those presented by Spitz (1982). This proposal sets out a study to examine this.

Further motivation for examining the question of dimensionality comes from recent theoretical accounts of the factors that influence the variability of these two forms of behaviour. Within the literature on individual differences and cognitive development, mechanisms that have been proposed to account for variation have included: speed of processing, metacognitive processes, inhibition and processing capacity. These mechanisms and the basis for attributing differences in intelligence to them are discussed in the next section.

**Mechanisms underlying individual differences**

**Speed of processing**

According to this account, within-age differences in intelligence can be explained in terms of differences in the speed at which information is processed (Case, 1985; Hale, 1990; Nettlebeck & Wilson, 1985) and is supported by behavioural data in which for example, reaction time and inspection time have been shown to correlate with IQ (Anderson, 1992; Deary & Stough, 1996; Jensen, 1985; Nettlebeck, 1987). Data from neurosciences further lend to this account. For instance, neurophysiological measures such as the average speed of evoked potentials and the speed of neural conductivity have
been shown to correlate with IQ (Anderson, 1992, 1999; Eysenck, 1986; Nettelbeck, 1987) suggesting a biological basis to differences in intelligence (Jensen, 1998).

**Metacognitive processes**

Sternberg (1983) has used mathematical models to support a theory in which it is asserted that metacognitive processes are the key factor underlying individual differences. Under this account, it is variation in the way lower-level processes are controlled (by processes that include goal awareness and strategy selection) that explains differences in intelligence.

**Inhibition**

The ability to inhibit is a further mechanism proposed to explain within-age differences in intelligence. Dempster (1991) has focused on this component of executive functions as the key underlying factor. This account draws on work that contrasts the performance of people with frontal lobe damage to healthy controls and finds differences in their ability to inhibit behaviour. The lack of ability to inhibit some behaviours results in interference and thus poorer performance on some cognitive tasks (e.g., the Stroop task). Neurophysiological studies showing differential activation of brain areas (Haier, White and Akire, 2003) and differences in the brain’s metabolic processes in high vs. low IQ individuals are cited in support of this mechanism (Haier, 1993).

**Mechanisms underlying cognitive development**

**Speed of processing**

According to others the development of reasoning ability can be attributed to increases in cognitive speed (Nettlebeck & Wilson, 1985; Hale, 1990; Case, 1985). Studies reporting linear relationships between children’s reaction time and adult’s reaction time support the view that differences in speed of processing plays a role in between-age differences
A more complex relationship between speed of processing and cognitive development is proposed by Case (1985). In this account, speed of processing interacts with brain maturation and experience. Speed of processing limits the hierarchical reorganisation of representations necessary for cognitive development.

**Processing capacity**

Halford, Wilson and Phillips (1998) describe this mechanism’s role in cognitive development, as one of increasing relational complexity. According to this theory, the complexity of strategies and the representations of concepts are limited early in development to fewer dimensions. As the number of dimensions applied to representations increases with age (1 in infancy and early childhood, to 4 in adulthood) more complex forms of reasoning are possible. This theory finds support from experimental studies in which performance over age increases with problems that differ on more than one dimension (e.g., the balance scale task). Additionally, Caryl (1994) argues on the basis of neurophysiological data that the registration of stimuli in intelligent individuals is a more complex form of representation. In other studies, correlations have been reported between brain properties such as whole brain volume (McDaniel, 2005), the proportion of white to grey matter (Gignac, Vernon & Wickett, 2003) and frontal grey matter volume (Thompson, Cannon, Narr, van Erp, Poutanen, Huttunen, Lonnqvist, Standertskjold-Nordenstam, Kaprio, Khaledy, Dail, Zoumalan, & Toga, 2001) to reasoning ability.

**Inhibition**

The increase in ability to form more complex representations over development has also been linked to the increased ability to inhibit irrelevant information and process relevant information (Bjorklund & Harnishfeger, 1990). This account is based on evidence from cognitive tasks and evidence that changes in brain properties such as myelination might reduce cross-talk interference (Bjorklund & Harnishfeger, 1990).
The question of dimensionality: one dimension or two?

Similarities between the mechanisms described above encourage consideration of whether cognitive development and individual differences may be represented as differences along the same dimension. If these two traditionally separate approaches to intelligence are found to share some common properties, then this raises the possibility of bridging the gap between these two fields of enquiry. Such differences in intelligence and cognitive development may be expressed as:

\[ H - L = O - Y \]

Box 2. Illustrating the notion: Higher – Lower ability = Older – Younger children

The theoretical accounts of the roles these mechanisms are proposed to play show overlap. However, the exact nature of how such mechanisms influence development and individual differences is not clear. Is speed of processing the same mechanism underlying variability in both individual differences and cognitive development? In order to make sense of how these mechanisms might operate, they must be implemented and tested within a formalised, explicit model. This proposal outlines a series of tests to examine the role of these mechanisms in explaining such variability.

Though computational models may allow one to test mechanistic theories, empirical studies that provide a direct comparison of these two forms of cognitive behaviour are essential. To these ends, I propose to match groups of children on mental ability and then compare performance on cognitive tasks. Comparing the performance of these groups, allows us to address the question of dimensionality: Do individual differences and cognitive development represent differences on one dimension, or two?

In the first instance, I propose to compare performance of ability-matched children of different actual ages on the subtests comprised within the BAS. However,
such comparisons using the BAS may not provide sensitive enough discrimination of the different processes that may underlie similar levels of performance (Karmiloff-Smith, Tyler, Voice, Sims, Udwin, Howlin & Davies 1998). The subtests on the BAS does not allow for fine grain analysis of reaction time or errors. Therefore the use of more accurate measures of cognitive ability is proposed. These more sensitive tasks consist of the balance scale, conservation of number and liquid, the Stroop task, word-priming and the Tower of London problem solving task. They include reaction time and accuracy data and thus allows for a more sensitive measure of cognitive ability (Karmiloff-Smith et al., 1998). The next section details how these methods will be applied in order to address the question of dimensionality.

**Experimental approaches**

This section describes two approaches to assessing individual’s abilities. In the first, the British Abilities Scales 2nd edition (CITATION) is proposed. This standardised test produces measures of core cognitive skills (i.e., verbal, non-verbal and spatial) and of academic achievement (i.e., number skills and spelling) using accuracy data. However, because there are many potential ways of achieving the same level of accuracy, this type of test may not be sensitive to differences in cognitive strategies. For this reason, it has been described as a test of ‘offline’ cognitive processes (Karmiloff-Smith et al., 1998).

The second approach involves the administration of a battery of computerised cognitive tests. These allow for the use of error data and reaction time measurements at the millisecond level. Karmiloff-Smith et al, (1998) argue this provides for a more sensitive, ‘online’ measure of cognitive ability. I adopt the use of both offline and online measures because they may allow a more complete assessment of cognitive ability.
1. The British Abilities Scales

The British Abilities Scales 2\textsuperscript{nd} edition (CITATION) offers a battery of tests suitable for individuals aged two years and six months (2:6) to seven years and eleven months (7:11) and five years (5:0) to seventeen years and eleven months (17:11). It provides measurements of reasoning and general conceptual abilities in addition to measurements of school achievement.

A score of overall mental ability is derived from performance on six separate subtasks, consisting of recall of designs, word definitions, pattern construction, matrices, verbal similarities and quantitative reasoning (see Figure 3 below).

Figure 3. British Abilities Scales II cognitive battery for ages 6:0 – 17:11
Using the BAS II children will be matched on overall mental ability (MA estimate = 8) and their performance on the subtasks of the BAS compared. If (as Spitz argues) cognitive development and individual differences represent two separate forms of cognitive variability, then comparisons of the profiles of these two groups would show little overlap. However, if these cognitive behaviours share a common property, then profiles of younger more able and older less able children would appear more similar. Figure 2a and 2b below give an illustration of each of these possible outcomes.

Figures 2a & 2b illustrating possible outcomes predicted by quantitative vs. qualitative differences in intelligence in two groups of children of different ages but equal mental age

2. The computerised tasks

Standardised tests will be used to ability match children of different ages, where their ability is taken to be their mean performance across the subtasks of the BAS. The children will then be given a computerised battery of more sensitive cognitive tasks. These tasks are described next.
The balance scale

According to Piagetian theory, cognitive development progresses through a series of stages that allow for increasingly complex behaviours across cognitive domains (Piaget, 1971). In this classic task of proportional reasoning the subject is presented with a balance scale and a number of weights on either side of a fulcrum. The subject is asked to predict which way the scale will tip, or whether it will balance when the supports (blue blocks) are removed.

![Figure 3. Example of a problem in the balance scale task](image)

In an attempt to characterise the possible stages underlying cognitive development, previous studies have sought to extract common rule-like behaviours by observing children’s performance. For instance, Siegler (1981) observed a tendency for younger children to ignore the distances of weights from the fulcrum and attend only to numbers of weights on either side. By contrast, slightly older children appeared to take account of information relating to distances but often seemed to ignore the numbers of weights on either side of the fulcrum. The emergence of these rule-like behaviours has been demonstrated also in a number of developmental computational models (van Rijn, Someren & van der Maas, 2003; McClelland, 1989 & 1995; Shultz, Schmidt, Buckingham & Mareschal 1995). Figure 4 below contains description of each of the proposed rules.
Different rules may offer predictions as to the relative time they need to be carried out (van der Maas & Jansen, 2003). For example, Rule 1 and Rule 2 both involve attending to just one dimension of the balance scale (either number of weights, or distance from the fulcrum) and therefore one may predict no difference in reaction times for problems of either type. Equally so, the Distant Dominant rule involves only immediate perceptual processing and therefore it too should require less time to processes than more complex rules. Rule 4, by contrast, would require more time compared to the simple perceptual rules as it involves comparing values of two sums (i.e., torque left vs. torque right).

This test was selected for the following reasons. If development and individual differences are unidimensional, then the performance of ability-matched children of different ages should appear similar both in terms of accuracy (i.e, stage of reasoning) and RT. However, if development and individual differences are on separate dimensions, then the performance of ability-matched children of different ages should show a divergence, perhaps in the stage of reasoning on the balance scale task or in their RTs. For example, older less able children may exhibit less sophisticated reasoning, or larger RTs.
**Conservation of liquid**

Conservation of liquid is the understanding that the actual amount of liquid does not change if it is poured from one container into a container of different dimensions. According to Piaget (1971), conservation appears around the age of 7 (at the beginning of the concrete operational stage). Children in this stage of development understand that changes to the perceptual properties of a container that holds some amount of liquid do not alter the actual volume. This is held to index the emergence of a more abstract, cognitive level of representation.

Children who have acquired conservation of liquid would conclude that the two containers in picture 11 of Figure 5 below hold the same amount of water. The younger, preoperational child on the other hand, would believe that the long thin container in picture 11 holds more water than the cone-shaped cup, even though it was originally believed the two cups in picture 1 had equal amounts.

**Figure 5. Stages in the computerised conservation of liquid task**
In the computerised, animated version of this task, subjects are initially presented with a picture of two containers of liquid (A and B) and asked to make a judgement as to which container holds more liquid, or whether they hold the same amount. After making their decision, the contents of the middle container (B) are poured into a new container (C), and the subject is again asked to indicate which container holds more water or whether they hold the same amount.

Although accuracy may be at ceiling for children matched on mental age of 8 (i.e., by this age, children should be able to conserve) differences in RT on this task may allow for discrimination between cognitive processes. For example, as the older, less able children have had more real world experience they may be faster on this task than younger, more able children.
Conservation of number

Conservation of number refers to the insight that the actual number in a set of objects does not change if the set is only compressed or elongated (Piaget, 1971). The perceptual elements of this problem confuse the preoperational child into thinking that a transformation that changes for example, the height of a row of objects has in fact altered its number. Subjects are required to make a judgement pre-transformation and post-transformation as to which set has more objects, or whether they have the same.

In picture 1 of Figure 6 below, two sets of coins on either side of a dotted line are presented. In this example, both sides have equal numbers of coins. A transformation is applied (pictures 2-7) in which one coin is added to the left-hand side and the set is compressed. Children who have not yet acquired conservation of number would believe that, following the transformation the side on the right in picture 8 has more coins.

In the computerised, animated version of this task, subjects are presented with a screen showing two sets of gold coins and asked to make a judgement as to which side has the greater number, or whether they have equal numbers. After making their decision, the child watches as one side is transformed and the subject is asked again, to indicate which side has the greatest number, or whether they have equal numbers.

Figure 6. Stages in the computerised conservation of number task
On this task, some transformations leave the number of objects unchanged whilst in others the number on one side is changed (either added to or subtracted from) the set. Levels of accuracy may not allow for discrimination between ability-matched children of different ages, but there may be differences in their RTs that may highlight differences in cognitive processes.

The Stroop

The Stroop forms one of a range of tasks that are assumed to tap components of executive function within which inhibition is considered to be a key control mechanism (see e.g., Miyake, Friedman, Emerson, Witzki, Howarter and Wager, 2000; Bull, Espy and Senn, 2004). The Stroop task offers a classic demonstration of the effect of interference from task-irrelevant information (Stroop, 1935). More specifically, interference is supposed to occur as a result of the lack of ability to inhibit one of two possibly relevant task dimensions. Typically, this task involves presenting word items to participants with the instruction to either read the word, or say the colour the word is printed in. When the task requires the subject to switch between dimensions attended to (e.g., read, then say colour) attentional control must be applied and information relating to the other dimension ignored.

For example, given the task to say the colour the following words are printed in: BLUE, GREEN, YELLOW, PINK, the inability to inhibit the other dimension (i.e., reading the word) becomes a source of interference in processing and is the basis for differences in accuracy and RT. One interpretation is that in order to successfully perform this task, the automatic tendency to read a word must be inhibited. Because executive functions are essential to so many forms of high-level cognitive behaviour, the ability to inhibit is closely related to differences in intelligence (Gray, Chabris and Braver, 2003; Chabris, 2006).

Differences in the ability to inhibit, as assessed by tasks such as the Stroop, have been correlated with differences in overall mental age (Bull et al., 2004).
If children of different ages who are ability-matched show differences in their performance on the Stroop task this would suggest that cognitive development and individual differences are not unidimensional. However, if RT and accuracy of these two groups appear similar then this would suggest cognitive development and individual differences may be represented as differences on one dimension.

**The Tower of London**

Originally introduced by Shallice (1982), the Tower of London has become a popular tool for measuring the problem solving abilities of children and adults. Both the Tower of London (ToL) and the task it originates from (the Tower of Hanoi) are argued to load heavily on executive processes (see e.g., Baughman & Cooper, 2006; Bull et al., 2004; Miyake et al, 2000).

In this task participants are presented with three different coloured balls and a board with three pegs of different lengths (see Figure 7). The height of the pegs constrains the number of balls that can be placed on them. The subject must move the balls around (using these pegs) in order to match a particular goal state, which remains visible at all times (top left-hand corner of figure 7). Two rules apply to this task, (1) only one ball may be moved at any time and (2) a ball can only be placed on a peg that has room for it.
Two key processes are considered to underlie performance on this task. These are the ability to inhibit and the ability to subgoal (see e.g., Baughman et al, 2006; Miyake et al, 2000). Inhibition is considered key to more efficient performance on this task as moves that initially appear to satisfy one goal may obstruct the next (e.g., Klahr and Robinson, 1981; Zelazo, Carter, Reznick and Frye, 1997). Subgoaling also forms an important part in achieving correct solutions, as individual’s are assumed to be limited in the number of moves they are able to look ahead (see e.g., Cohen & O’Leary, 1992; Baker, Rogers, Owen, Frith, Dolan, Frackowiak and Robbins, 1996). The ability to subgoal efficiently has been linked to both working memory and intelligence (Morris, Ahmed, Syed & Toone, 1993; Gunzelmann & Anderson, 2003).

The role of inhibition has been demonstrated in computational simulations of the Tower of London task and has been shown to account for differences in performance between 4-5 and 5-6 year olds (Baughman et al., 2006). It is possible that differences in the ability to inhibit underlie differences in performance between groups of different ages but equal mental age.
Differences in the ability to subgoal may be discernable from RT and the total number of moves made to complete a problem. If comparisons of these measures between ability-matched children of different ages appear different, then this would indicate cognitive development and individual differences are separable forms of cognitive variability. However, if variability underlying development and individual differences are unidimensional then comparisons of these groups performance would appear similar.

**Word priming**

Word priming tasks offer a possible window to explore how language may be organised within a cognitive system, as well as the dynamics of activity spreading through that system. Word priming studies generally show robust differences in naming-times for word items preceded by a related prime (e.g., Nation & Snowling, 1999). For example, the speed with which a subject names the target word BISCUIT is faster if preceded by a related priming word such as MILK than if preceded by an unrelated prime such as PENCIL. Priming effects can be found using words that are related associatively (e.g., BREAD - BUTTER) or categorically (e.g., SCISSORS - KNIFE).

A number of theories exist that attempt to account for this phenomenon. For instance, spreading activation theories (e.g., Anderson, 1983; McNamara, 1994) provide an account in which it is supposed that activation spreads between connected nodes within a semantic network. Words that are semantically related prime other words that share meaning in this network, thus accounting for the faster naming-times.

The speed of processing information and responding on this task may be linked to the rate of activation spread. Therefore, comparisons between ability-matched children of different ages may show differences on RT and accuracy on this task. Such differences would suggest separate dimensions relating to cognitive development and individual differences.
Combining offline and online measures

This section has outlined two approaches to comparing cognitive abilities between ability-matched children of different ages. The difference in sensitivity between offline and online tasks can be illustrated by considering the pattern construction task of the BAS and the Tower of London. Both involve the use of non-verbal reasoning and spatial visualisation and both make use of time taken to complete a problem.

However, they differ in the following ways. Whereas the Tower of London task provides analysis of the total number of moves made, the number of attempts, the number of rule-breaks and the sequence of moves made on each problem, the pattern construction task provides only an overall completion time and which area of the pattern was incorrect. Whereas the TOL does not impose time restrictions and so allows subjects to experiment with switching strategies, the pattern construction task includes time constraints (up to a maximum of 120 seconds). Whereas the TOL task allows partially completed problems to be treated as partially correct (e.g., only one, or two balls in their correct place), the pattern construction task allows only for correct (score=1), or incorrect (score=0) solutions. This allows the TOL to reveal potential variability in non-verbal and spatial reasoning processes where the pattern construction task may not. Such variability might be masked in the pattern construction task because it does not allow for fine-grained analysis of RT, error and number of moves made.
Experimental methodology

Design

A quasi-experimental design is employed with the between-subjects factor being younger, more able vs. older, less able children and the within-subjects variables consisting of (a) the core scales, diagnostic scales and achievement scales from the British Abilities Scales 2nd edition (Elliot, 1996) and (b) the battery of computerised tasks described above.

Participants

Thus far, data for 40 primary and infant school children, 35 secondary school children and 30 adults have been collected. Of the 40 primary and infant school children recruited from two schools in North London, 20 were aged 5-6 years old and 20 aged between 10-11 years old. This sample included an even split of males and females. Selection of these 40 children was based on their rank in performance on class tests of numeracy and literacy. Each school provided 20 children from the following classes: from year 1 (5-6 year olds), five children from the top-end of two classes were selected; from year 5 (10-11 year olds), five children from the bottom-end of two classes and who were not of special educational need (SEN) were selected.

Thirty-five secondary school children, from one school in Southampton were also recruited. Selection of these children was based on their mean scores on the Cognitive Abilities Tests (data supplied by the school). Of these 35 children aged 12-16, an approximately even split of boys and girls was obtained (males=17, females=18). Participants were selected on the basis of school administered cognitive abilities test (Thorndike, Hagen & France, 1985). Children with mean standardised age scores of 74-88 were selected for the lower-ability group and those with scores above 112, were selected for the higher-ability group.
A final sample of 30 adult control subjects is currently underway. To date, a total of eleven adults have been tested on the battery of computerised tasks and Raven’s Progressive Matrices (Raven, 1998) and the British Picture Vocabulary Scale (Dunn, Whetton & Pintilie, 1982).

**Apparatus / Materials**

One Apple Macintosh laptop (1.33 GHz PowerPC G4 processor) and one HP laptop (1.4 GHz Intel Celeron M processor) were employed for the computerised tasks and were connected to a Elo Systems Touch screen monitor, with a stylus. One set of high definition Sennheiser headphones, a Logitech digital microphone, a RS750 response box and a pair of Logitech external speakers was also used.

The BAS has two parts, core skills and optional diagnostic and achievement scales. All of the cores scales were administered. These comprised of the following subtests (1) recall of design, (2) word definitions (3) pattern construction, (4) matrices (5) verbal similarities (6) and quantitative reasoning. The tests included under the diagnostic and achievement scales consisted of (1) recall of objects, (2) speed of information processing (3) recall of digits forward and (4) recall of digits backwards (5) number skills and (6) spelling.

**Procedure**

Subjects were tested individually in a quiet room in slots of approximately 30-40 minutes over a period of four months. The total time for each child was approximately 3 hours and testing for each child was completed within one week. Each child received a randomised order of computerised tasks interwoven with sections of the BAS II. Figure 8 below illustrates the task presentation for one subject (experimental tasks are highlighted in pale green, computerised tasks in pale blue).
For each of the computerised tasks (except the conservation of liquid), the procedure followed this format:

1. An instruction video was played outlining the nature of the activity and the type of response that was required;

2. A practice trial was completed where subjects were required to demonstrate that they had understood the instructions correctly;

Subjects received a physical demonstration of this task to facilitate generalisation from physical objects to the computerised 2-dimensional representation of cups of liquid on screen.
3. Subjects were given the opportunity to ask any questions, or repeat the practice trial;
4. Subjects performed the real trial

**The balance scale**

Subjects were shown an animated video that gave instructions on this task and then given six test items to demonstrate understanding of the task requirements. They were required to touch a button on a touch screen that corresponded to their belief about the outcome of each problem. Upon touching one of three buttons (tip left, balance, tip right) feedback was given visually in the form of animated movement of the balance beam accompanied by auditory feedback, in the form of a correct (fanfare) or incorrect (buzzer) noise.

A total of 96 problems were randomly administered in 8 blocks of 12, thus allowing for short breaks between blocks. The total problem set consisted of 16 different examples of six different problem types (see, Richardson et al., 2006) and were counter-balanced for outcome (i.e., tip right, left or balance, see below).

The six problem types:

1. **Balance problems**: The same numbers of weights are positioned at the same distances on both sides. The scale balances
2. **Weight problems**: Different numbers of weights are placed at the same distances on both sides. The scale tips to the side with most weights.
3. **Distance problems**: The same numbers of weights are placed at different distances on each side. The scale tips to the side with weights the greatest distance from the fulcrum.
4. **Conflict Balance**: Different distances and weights. The scale balances.
5. **Conflict Weight**: The number of weights and their distances from the fulcrum vary. The side with the greater number of weights closer to the fulcrum tips.
6. **Conflict Distance**: The number of weights and their distances from the fulcrum vary. The side with fewer weights and the largest distance from the fulcrum tips.

The number of correct responses as a percentage was displayed for the subject at the end of each block and an overall percentage was given at the end of the task. The dependant variables for this task are: accuracy on each of the six problem types, RT for each problem.

**Conservation of liquid**

A practical demonstration of this task was performed. Subjects were presented with two identical containers filled with equal amounts of water and asked to make a judgement as to which container held more or whether they held equal amounts. They then witnessed one container being poured into a third container and asked to make the same judgement.

Following the practical demonstration, subjects were given the computerised test version with four test items to demonstrate understanding of the task requirements. Again, they were required to touch a button on a touch screen as to which container held more liquid or whether they held the same. Upon touching one of three buttons (left more, same, right more) a series of animations were initiated that involved the container on the right moving to a position in the middle of the screen, while a new third container was introduced. The middle container then poured its contents into the new container (with accompanying sound effects) and returned empty to the middle position. Subjects were required to touch a button again to indicate which container they then thought held more water, or whether they held the same amount.

A total of 36 problems of six different problem types were administered, balanced for outcome (left more, same, right more). These were:

1. **Same-Same**: Containers are of same volume, start perceptually same and end perceptually same
2. **Same-Different**: Containers are of different volume, start perceptually same, end perceptually same
3. **Different-Same**: Containers are of same volume, start perceptually same, end perceptually different
4. **Different-Same**: Containers are of same volume, start perceptually ambiguous, end perceptually ambiguous
5. **Different-Same**: Containers are of same volume, start perceptually different ambiguous, end same perceptually
6. **Different-Different**: Containers are different in volume, start perceptually different, end perceptually different

The dependent variables for this task are reaction time and accuracy on each of the problem types.

**Conservation of number**

A practical demonstration was first performed. Subjects were presented with two rows of equal numbers of counters and asked to make a judgement as to which row had more counters or whether they had equal numbers. They then witnessed a change to one row and were asked to make a similar judgement.

Following an animated video of the instructions for this task, subjects were given four test items to demonstrate understanding of the task requirements. Participants were required to touch a button on a touch screen as to which side had a greater number of objects or whether they had the same. Upon touching one of three buttons (left more, same, right more) a series of animations would be initiated that involved a transformation to the coins on one side of the screen. A hand would appear and either (a) just change the appearance of those coins (elongate or compress the row), or (b) alter the number of coins (add or subtract). Subjects were required to touch a button again to indicate which side they then thought had more coins, or whether they had the same number.
Four problem types consisting of 24 problems were administered in which 6 different transformations appeared. These consisted of: elongation, compression, subtraction, addition, elongation and subtraction, compression and addition; and were balanced on outcome (left more, same, right more). The four problem types were as follows:

1. **Same-Different (start):** Rows have different number, start perceptually same, end perceptually same
2. **Same-Different (end):** Rows have different number, start perceptually different, end perceptually different
3. **Different-Same (start):** Rows have same number, start perceptually different, end perceptually same
4. **Different-Same (end):** Rows have same number, start perceptually same, end perceptually different

The dependent variables in this task are reaction time and accuracy on each of the four problem types.

**The Stroop**

Subjects were first shown an instruction video of the task and were then given a set of four word naming and colour naming items of each problem type to demonstrate understanding of the task. Subjects were presented with a series of words that were displayed individually on screen with the instructions to either (a) read the word (and ignore the colour the words are written in), or (b) say the colour the word is printed in (but not read the word). The order of tasks (i.e., read or name the colour of the words) was randomised for each subject.

The stimuli consisted of a total of 45 word items presented in four blocks of fifteen word items each and included five different types of items:
1. **Colour-Conflicts:** Colour words written in conflicting colours (CC) e.g., the word GREEN written in blue letters.

2. **Colour-Non Conflicts:** Colour words written in non-conflicting colours (CNC) e.g., the word RED written in red

3. **Colour-Neutral:** Colour words written in neutral colour, i.e., black (CN) e.g., the word BLUE written in black letters

4. **Word-Colour:** Non-colour words written in colours (WC) e.g., the word KING written in yellow

5. **Word-Neutral:** Non-colour words written in neutral (WN) e.g., the word TABLE written in black

There were five colours and five non-colour words word items. The colours comprised of: “PINK”, “RED”, “GREEN”, “YELLOW” and “BLUE”. The five non-colour words comprised of: “TABLE”, “KING”, “BABY”, “RABBIT” and “CAR”. These were counter-balanced to appear in the following colours: green, yellow, red, pink and blue. Items within the neutral condition appeared in black.

Subjects first heard a flat tone that signalled the onset of a stimulus and 1000 ms later, a word item was displayed on a screen. They were required to name out loud either the colour of the letters or to read the word. Responses were recorded digitally as .wav files, from which naming times and response accuracy would be assessed. This was used in preference to a voice-activated microphone because certain background noises (e.g., coughing, or child movement) might trigger incorrect response times. Recording as a .wav file also allows better accuracy in instances where the child hesitates or when they change their response during the naming (e.g., “grrrr…blue”).

The dependent variables are RT and accuracy for each of the problem types.
The Tower of London

Subjects first watched an animated instruction video of the task, before completing 4 test problems requiring a minimum of 1 and 2 moves.

Three rules apply to this task:

1. If a peg doesn’t have space for a ball it can not be placed on it
2. A ball can not be moved if another ball is on top of that ball
3. A ball can only be placed on a peg (not anywhere else on screen)

These rules were illustrated by asking the subjects to attempt to break them. Subjects observed that (1) a ball which was placed on top of a peg that did not have space for it was returned to its original position (2) a ball under another ball could not be moved and (3) a ball left in white space and not on a peg, was also returned to its original position.

Following the test problems a total of 16 problems were administered randomly. These consisted of four problems of four different levels of complexity (requiring a minimum of 3, 4, 5 and 6 moves respectively) and were counter-balanced on end configurations (flat configurations and tower configurations).

The dependent variables on this task consist of accuracy and RT for each problem, the number of attempted rule breaks, the number of attempts at each problem and the number of balls in correct position (allowing for partially completed solutions to be scored).

Word priming

This computerised task was developed by Leech et al., (2006), to demonstrate word-naming differences in children of similar ages (5-9 years old). No modifications were made here. In this task, subjects were told to listen to a series of paired words, spoken first by a woman and then by a man. They were instructed to attend carefully as although
the woman always said a real word, the man sometimes said a real word and sometimes said a made up word. Subjects were required to respond to the man only. They were told to decide as quickly as possible whether he had said a real word or a non-word, by pressing one of two buttons on a response box (green for real word, red for non-word). Subjects first heard four paired word items played through the computers speakers to demonstrate understanding of the task. After the test items had been successfully identified, subjects put on headphones and began the task.

A total of 60 priming words were counter balanced and paired with target words. The primes and targets were associated either by function, category or with a non-word. Target words followed the priming word 1000ms later and a new trial was presented as soon as a subject made a response, or every 3 seconds which ever came sooner.

The dependent variables in this task are accuracy and RT for each of the prime-target associations.
Computational methodology

Computational models force specification of a process. Theoretical terms such as speed of processing, inhibition, or processing capacity must be encoded as parameters. Current research questions the relationship between cognitive development and individual differences. Based on principles derived from neural information processes, connectionist models allow verbal theories of cognitive and developmental processes to be fleshed out more fully (see, e.g., Elman, Bates, Johnson, Karmiloff-Smith, Parisi & Plunkett, 1996). Connectionist models are systems that incorporate a range of parameters that guide their learning and thus may provide the basis for addressing issues of learning and development. Parameters govern the pattern of interconnectivity between units, the input and output representations, the type of learning algorithm applied and the features the training set holds. These influence the efficiency of learning and so allow us to study potential explanations of variability.

To a large degree, connectionist models have focused on exploring questions of development within specific domains of cognitive activity. They have been less concerned with theories relating intelligence to specific properties of the brain. With the number of speculative claims increasing as to the possible underlying mechanisms of general intelligence (see e.g., Thomas & Karmiloff-Smith, 2003), it is time now to start exploring how these hypothesised mechanisms may operate in producing cognitive variability. To these ends, this research project aims to address the following question: Within a family of normative models of performance on a range of cognitive tasks, is there one single parameter that can make a system display more, or less intelligent activity?²

Progress has already been made in this direction. For example, Richardson, Baughman, Forrester and Thomas (2006) tested multiple alterations to a network’s ability to learn the Balance scale task. These included manipulations to (a) the number of hidden

² Where intelligence is operationalised in the way described in the previous section
layers, (b) the number of units within a layer, and (c) the slope of the sigmoid within hidden units. Of some importance were their findings that whilst increased number of units within a layer increased the *capacity* of the network, it did not add to its *representational power*. However, it is not clear how such manipulations will affect the performance of models within other cognitive domains.

Such attempts to elucidate the relationship between altering properties of a system and their consequent effects on intelligent activity may allow a clearer understanding to develop of the possible relationships between properties of the brain and individual differences in general intelligence.

**The family of models**

For each of the administered computerised tasks a computational model will be implemented. In most instances, there already exists an established model that accounts for normative behaviour on these tasks. Thus, the tasks to be modelled are; Balance scale (McClelland, 1989), Conservation of liquid & number (e.g., Shultz, 1998), the Stroop task (Cohen, Dunbar, & McClelland, 1990), the Tower of London (initially guided by Simen, Polk, Lewis and Freedman, 2002), and word priming (Hinton and Shallice, 1991; Plaut and Shallice, 1993). The first phase of modelling will be to replicate these normal models.

**What manipulations will be performed on these models?**

Manipulations to these models will include alterations to (1) the learning rate, (2) the number of units within hidden layers, (3) the number of hidden layers, (4) the level of discriminability within units, (5) the type of representations given to input and output and, (6) the features of the training regimen.

By varying these parameters in normal models one may reproduce the observed variability in the empirical data, either by age, ability, or both should they fall on a single
dimension. A target phenomenon to explain are the differences that Spitz reported between the younger more able and older less able children. This includes the younger children’s increased ability on tasks involving abstract reasoning and older children’s increased ability on tasks. The aim of these manipulations then, is to see if such differences can be simulated in models of these tasks.
Timetable

To complete this research, this proposal outlines the following timetable (of which steps 1-5 have been completed):

1. Schools will be contacted and presentations given to Heads between February and April 2006.
2. The computerised tasks will be set up using MATLAB during the months of April and May 2006.
3. The piloting begins on children (aged 5-10) and adults, during May 2006.
4. Main testing is estimated to take place from June 12th until the end of 2006 academic year (July 21st, 2006).
5. Testing at one secondary school is arranged for September 18th – November 10th 2006.
6. Following the completion of these testing phases, the scoring of BAS II data and data from the computerised tasks will begin. This is expected to last from mid-November until early May 2007.
7. In parallel with the scoring, computational modelling will begin. Models of each of the tasks will be implemented and a regime of parameter tests will be established. Due to the number of models required and the number of parameter manipulations necessary, it is estimated that modelling work will continue until November 2007.
8. Comparisons between experimental and computational data are expected to take place from June 2007 with any additional modelling this may reveal necessary being carried out by November 2007.

These steps necessary to complete the research project are presented in Figure 9 below.
Figure 9. Timetable for completion of research

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