THE COGNITIVE BASES OF MENTAL STATE REASONING IN ADULTS

By

ADAM WERNER QURESHI

A thesis submitted to

The University of Birmingham

for the degree of

DOCTOR OF PHILOSOPHY

School of Psychology

The University of Birmingham

December 2008

ABSTRACT

An individual differences study with 154 adult participants was used to investigate the relationship between inhibitory control and theory of mind (ToM), using structural equation modelling. The battery of executive function tasks was found to tap two separate inhibitory components, response inhibition and response selection. This went against the literature suggesting one inhibitory factor or two components of response inhibition. The two ToM tasks used were both level-1 perspective taking tasks with similar demands, so were expected to tap the same latent variable. The results showed no correlation, suggesting that the tasks might tap separate components of ToM. These were characterised as a fast, inflexible component and a slower flexible component. The relationships between the response inhibition factor and the two ToM tasks were similar, suggesting that they also had executive requirements in common. Additional dual-task studies suggested that response inhibition was required for resolving conflict resolution between perspectives. Altogether it is argued that the results are more consistent with the existence of two distinct systems for theory of mind, than with one system that makes varying demands on executive function in a task-specific manner. This two-system interpretation provides a parsimonious explanation for findings that infants and primates are able to pass perspective taking tasks and that adults reliably make errors in simple ToM tasks.

DEDICATION

To my grandparents:

Jutta Sammler
Werner Sammler
Abdul Rehman
Akhtar Begum

ACKNOWLEDGMENTS

I would like to thank my supervisors, Ian Apperly and Dana Samson, and everyone in the School of Psychology, University of Birmingham; the University of Birmingham for the studentship; Coventry University for the teaching experience; and all of my family and friends, but Sarah Thomas especially for her support throughout.

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1. Literature Review

Theory of Mind

The ability to understand that other agents have different beliefs, desires and knowledge to oneself is a crucial component of what has come to be termed ‘theory of mind’ (ToM) (Premack & Woodruff, 1978). ToM also incorporates the ability to predict another’s behaviour based on their (different) beliefs, desires or knowledge. It is therefore critical in being able to socially interact with others.

Research (for example, Gopnik & Astington, 1988; Wellman, Cross and Watson, 2001; Wimmer and Perner, 1983) has suggested that ToM is an ability that develops through in early childhood, and may be fully developed from about the age of four, as at this approximate age children are able to pass standard false belief tasks. Investigations into when children are able to predict other people’s behaviour, based on their ability to realise that other people have different beliefs and desires to themselves, started in the 1980’s. Before this, the work of Jean Piaget (Piaget & Inhelder, 1967) was the dominant theory in children’s development. Piaget’s theory worked on the principle that children are very egocentric (that they do not have the mental ability to understand that others have different opinions and beliefs from themselves), and that is why they can not understand another’s perspective, belief or desire until approximately seven years old. ToM, as it is termed now, was explained as occurring as part of the general move away from egocentrism at this time.

The emphasis on egocentrism (and the move away from this at seven years old) as being an overall explanation for development of the understanding of others’ beliefs was challenged when Premack and Woodruff published an influential paper in 1978 questioning whether animals, specifically chimpanzees in their case, could have a ToM as it is defined in humans. As part of a commentary on the paper, the philosopher Daniel Dennett proposed a paradigm that could show whether chimpanzees had a ToM (Dennett, 1978). The example used by Dennett took the form of a Punch and Judy show. Children are excited at the point at which Punch is about to throw a box over a cliff. The children have seen Judy escape from this box whilst Punch’s back was turned, so the excitement is based on the children knowing that Punch falsely believes that Judy is still in the box. This shows that they have some understanding of false belief. This paradigm was the basis of the classic false belief task of Wimmer and Perner (1983). This study, and the hundreds of replications that have also been conducted, showed that children were able to predict the actions of someone who had a false belief (which was different to their own) at around the age of four. This finding was consistent across many different methodological variations and cultures (Wellman, Cross & Watson, 2001).

In contrast to the extensive amount of research in children, there have not been many studies that have focused on ToM abilities in adolescents and adults, and those that have tend to focus on clinical samples. The assumption seems to be that once ToM has developed in children then it is fully formed and no longer develops any further. There is evidence from adolescent and from adult studies (from both clinical and typical samples) that aspects of ToM do develop past childhood (activated areas of the brain during ToM tasks are different in adolescents than in adults; Blakemore, 2008), and in adults, errors are made in ToM tasks that should not occur if the ability was fully developed in childhood (Keysar, Lin & Barr, 2003). There is also evidence that there are links between ToM and executive function, and that ability in both declines with age (German & Hehman, 2006; Zelazo, Craik & Booth, 2004). There is also evidence that language is also critical in ToM (de Villiers & de Villiers, 2002; Newton & de Villiers, 2007), and this implies that as language develops beyond four years old, ToM may also develop beyond four years old.

Moreover the established view of ToM as developing through childhood and being fully developed by (approximately) age four does not adequately explain the evidence that infants can pass perspective taking tasks, as there are some studies that seem to show infants below this age passing perspective taking tasks that should be beyond their capabilities (Onisihi & Baillargeon, 2005; Sodian, Thoermer & Metz, 2007).

Therefore there are reasons for doubting this simple picture of ToM based exclusively on development from two to four years old. Evidence shows that infants are able to exhibit some ToM abilities, but without having the underlying executive function and language capabilities that are thought of as necessary for ToM. This account also does not explain the errors made by adults in what appear to be relatively simply ToM tasks (Keysar et al., 2003). There is scope for either a refinement or redefinition of the current model of ToM. The current study aims to test adult participants on ToM tasks that are similar to those that infants can pass and on those on which they make errors, to compare the patterns of results.

Development of ToM

Pioneering work by Piaget (1937 / 1954) focusing on children provided evidence that children were apparently unable to understand that other agents had differing perspectives to their own – this was treated as a case of egocentrism. Children were shown a table with three model mountains placed on it, They sat at the table, and were asked to choose a picture that represented what a doll, sitting at a different position at the table, could see. Children less than six years of age tended to choose the picture that represented what they could see, not what the doll could see, thereby exhibiting egocentrism. Later work by McGarrigle and Donaldson (1975), with more child-appropriate stimuli[1], found that children were able to understand that other agents had different perspectives to their own. In their experiment children were shown a model brick wall (in the form of a cross), two policeman dolls and a robber doll. The children were asked to place the robber where the policemen could not see him. In order to pass this task, children must understand what the policemen could see. Children of 45 months were able to pass the task, showing that they could understand other agents' perspectives, contrary to Piaget's findings. However, the level of perspective taking required by Piaget's experiment may be more complex than that required by McGarrigle and Donaldson (1975). The experiment of McGarrigle and Donaldson (1975) requires level one perspective taking. This is the ability to understand that the content of what one can see can be different from the content of what another sees in the same situation. The three mountains experiment required level two perspective taking. This requires the understanding that the child and another person can see the same thing simultaneously from different perspectives. This suggests that children can pass simple perspective taking tasks. The difference in findings between studies with differing experimental paradigms is an occurrence that will be returned to later.

[1] Although as Piaget worked in Geneva, Switzerland, the three mountains task may have made sense to local children.

Wimmer and Perner (1983) developed the classic ToM paradigm, the false belief task, in order to improve on the procedure of Piaget and of McGarrigle and Donaldson. The task presents children with a scenario in which a puppet character places a chocolate bar in Location A, and then leaves the scene. Whilst that character is off-screen (and so oblivious to any actions then taking place), the mother of the character enters the scene and moves the chocolate bar from Location A to Location B. The puppet then returns to the scene, and the child is asked where the puppet will look for the chocolate. The correct answer is Location A, as that is where the puppet thinks the chocolate is. The answer of children before ages four to five usually is Location B – as that is where they know the chocolate is, and they believe that the puppet knows that too. This could be due to not understanding that the puppet has its own beliefs or knowledge, or because of difficulty in distinguishing their own knowledge from that of the puppet.

Other tasks that are used in developmental studies include unexpected-contents tasks (where the child is shown a tube of Smarties, and asked what they think it contains – their answer is Smarties. They are then shown the contents, which are pencils. They are then asked what their friends would think was in the tube, and their answer (before ages four to five) tends to be pencils (Gopnik & Astington, 1988). As a result of these findings, ToM was suggested to be a novel cognitive skill (or perhaps a domain-specific module; Leslie, 1987) that develops through childhood. Other suggestions are that children have difficulty in acknowledging that other agents have different beliefs to themselves because this ability requires some level of detachment from reality, and because children themselves are still getting to grips with reality (Mitchell & Lacoheé, 1991). Both of these standpoints suggest that what we term as ToM is present in children after the age of approximately four.

Some evidence to the contrary comes from a study by Ruffman, Garnham, Import and Connolly (2001). In this study children are given a false belief task, but their level of confidence in their responses is measured using a 'betting' system on their choice of one of two possible locations. If they were 100% confident in their explicit location choice they placed all of their bet tokens on to that location choice, and if they were not they would place the majority on their explicit location choice, and some on the alternate choice. The pattern of results through the age groups tested showed that the youngest participants tended to explicitly choose the incorrect location (not passing the false belief task, and thinking that the character knew what they knew), and also were confident in this choice, placing all or most of their tokens onto the incorrect location. The four to five year olds still tended to choose the incorrect location explicitly, but would be more likely to place some tokens on the correct location – this was argued to show some level of implicit knowledge of the correct location, and hence an implicit knowledge of false belief. The next pattern of results was explicitly choosing the correct location, but still putting some tokens on the incorrect location – this was taken to show that there was still some uncertainty in using the false belief knowledge. The oldest participants chose the correct location explicitly, and also were confident in their decision, placing all their tokens in that location. This evidence seems to indicate that children have implicit knowledge of false beliefs at an earlier age than expected, and that this implicit knowledge exists at a time when they explicitly fail false belief tasks. Equally, the initial stages of false belief understanding are characterised by low confidence in that understanding, before full understanding occurs.

Other studies (Onisihi & Baillargeon, 2005; Sodian et al., 2007) have found evidence, using non-verbal tasks, that infants of 14 and 15 months are able to predict an actor's behaviour using what may be level-one perspective taking or perhaps false-belief understanding. Level-one perspective taking is the ability to understand that the content of what one can see can be different from the content of what another sees in the same situation. Sodian et al. (2007) used a non-verbal paradigm that involved measuring how long infants looked at an actor reaching for an object. Their study also used a screen to hide objects from the actor, whilst keeping them visible to the infant. Familiarisation trials established a preferred object (of two, the other being a distracter object. The actor could see both objects) that the actor reached for. Experimental trials had the distracter object in the position of the preferred toy, while the position of the preferred object toy was either visible to the actor or not. The actor then reached for the distracter object. Infants spent less time looking in trials where the preferred object was not visible to the actor than in trials where the preferred object was visible to the actor. This was said to indicate that the infant understood that the actor could see the preferred object in the latter trial, so the reach to the distracter object was unexpected, whilst in the other trial they understood the actor could not see the preferred object, so reaching for the distracter object was expected. They were therefore exhibiting some level-one perspective taking abilities, as they were able to represent the actor's viewpoint independently from their own.

Onishi and Baillargeon also used a non-verbal task that used the violation-of-expectation method. Infants were shown a video of an actor, facing them with a visor covering their eyes, with two boxes in front of them. The boxes could be hidden from the actor by a screen, but were always visible to the infant. A (target) toy could be present in one of the boxes, and infants were assessed on how long they looked at the location where the actor reached (so where the actor thought the toy was present). The premise of the violation-of-expectation method is that the participant will look longer at an occurrence that violates what they think should occur. Familiarisation trials established that infants looked longer at reaches by the actor to the location where the toy was not present (as they should reach for where the toy was present). True and false belief trials (achieved by the movement of the toy between the boxes either with or without the knowledge of the actor) showed that infants spent longer looking at reaches that violated their expectation of where the actor reached, according to the actor's belief. In the true belief trial, infants looked longer when the actor reached for the incorrect location, and in the false belief trials infants looked longer when the actor reached for the correct location. This extends the work of Sodian et al. (2007) to what appears to be false-belief understanding.

Both methodologies remove any demand on language (that is usually requisite to pass ToM tasks), and both reduce demand on executive function (as the infants are not required to do anything that is contrary to their natural behaviour that then might require effortful control – they simply look where the actor reaches). This does not need the infant to exhibit an explicit understanding of perspective taking, but allows a measure of their implicit understanding to be taken. There is also no requirement to explicitly predict future behaviours based on their implicit understanding. All of this evidence points to there being a ToM capability present in humans at a much earlier age than was first thought when using standard false belief tasks (and variations on it) such as that of Wimmer and Perner (1983). However, the fact still remains that children still explicitly fail standard false belief tasks before the age of approximately four years of age. There have been differing reasons put forward to explain these findings: some argue that the non-verbal infant studies can be explained by, for example, infants using behavioural rules (such as looking where the other person looked last). This reasoning suggests that ToM, as it is defined by Premack and Woodruff (1978), is not present in infants, and is only shown in children when they are at least four years old (Ruffman & Perner, 2005). This change is assisted by other developments in language (Astington & Baird, 2005) and executive function (Carlson & Moses, 2001; Carlson, Moses & Breton, 2002; Carlson, Moses & Claxton, 2004). Others suggest that there is evidence for ToM being present in infants, at the very least as a conceptual framework for the ToM shown explicitly at age four (Leslie, 2005; Onishi & Baillargeon, 2005), that is in turn given as backing for ToM being a specific innate module that is present from birth. The developmental literature remains unresolved on this controversy.

The role of language

Whether ToM is early- or late- developing, there is evidence to suggest that the ability to pass standard false belief tasks is connected to both language and executive function. Language has been established as an important correlate to false belief understanding, that has been investigated because of the individual differences found in the age of false belief understanding occurring (although four years old is the approximate age, this varies between three years and five years of age). Individual differences in language ability have been proposed as a factor affecting individual differences in understanding false beliefs (de Villiers & de Villiers, 2002; Milligan, Astington & Dack, 2007). There have been links made between pragmatics and ToM, in that in order to understand a speaker's utterances sometimes requires some level of understanding of their mental state and intentions at that time (Sperber & Wilson, 2002). Links between semantics and ToM have also been made, specifically in the meaning of mental state words such as "think" or "want" (Moore, Pure, & Furrow, 1990), and also in more general semantic knowledge (Milligan et al., 2007; Ruffman, Slade, Rowlandson, Rumsey, & Garnham, 2003). There has also been a relationship proposed between grammar and ToM. This relationship is based on the hypothesis that we represent others' beliefs in our mind in the form of a proposition. Evidence (mainly from children: de Villiers & Pyers, 2002) has suggested that in order to represent a belief one needs to be able to process embedded complement clauses (for example ‘Max thinks the chocolate is in the cupboard’) which is how beliefs are expressed verbally. This whole sentence can be true, even if the embedded clause (chocolate is in the cupboard) is false, and so it can be a true report of false understanding. This may facilitate false belief understanding. Understanding of embedded relative clauses (‘The woman pushed the man *that opened the box*’: Smith, Apperly, and White, 2003) has also been linked with belief reasoning, which points to a more general role for embedded grammatical structures.

There are different reasons put forward for the relationship between language and false belief: some suggest that it is because the standard false belief tasks require some level of verbal ability to pass. An analogous explanation is that language is required for the domain general cognitive processes that underlie false belief understanding to be used. These views suggest that language is useful to false belief understanding in terms of expression and implementation, but that it is not necessarily key to actual development (Bloom & German, 2000; Carlson & Moses, 2001).

There is an alternative viewpoint that posits language as a causal element in false belief development (de Villiers & de Villiers, 2002). The meta-analysis by Milligan et al. (2007) on the relationship between language and false belief in the developmental literature found an overall relationship between language ability and false belief performance, and additionally found that the relationship between early language ability and later false belief performance was stronger than the reverse relationship. The analysis compared different types of language ability: semantic ability (lexical knowledge and discourse semantics (meaning of words beyond lexical)); syntactic ability (linguistic structure); receptive vocabulary; general language ability (semantic and syntactic ability); and memory for complements. Memory for complements tests the understanding of embedded complement clauses.

Examination of the different types of language ability showed that only general language ability (as measured by the Test for Auditory Comprehension of Language and the Test of Early Language Development I, II, and III) was significantly related to false belief performance (in post-hoc tests) (Milligan et al., 2007). This may be due to the general language measures being the broadest in terms of potential types of language ability being tapped. This is compared to the non-significant post-hoc test relationships between receptive vocabulary, semantics, syntax, and memory for complements and false belief, all of which could be said to measure a more specific type of language ability. However, the largest amount of variance explained in false belief performance was by memory for complements. The fact that language is related to false belief performance may indicate that one of the reasons why infants are unable to pass standard false belief tasks is due to their lack of linguistic capability and the abilities that this engenders. This meta-analysis did not cover conversational linguistic abilities due to the difficulty of measuring competence in such an area (conversation is a joint action, not an individual process), and the analysis focused on experimental language measures for that reason. This means that an area that could contribute to the development of ToM was not considered.

The role of executive function

Another area that has been investigated as a correlate to false belief understanding in children is executive function. Executive function is another complex set of abilities and has been defined as an overall function that includes processes such as planning, attention, inhibition, and working memory, in order to plan and achieve goal-directed behaviour (Norman & Shallice, 1980; Shallice, 1982). This definition gives some indication of the issues of trying to decide what aspects of executive function could be related to false belief understanding, and likewise, what tasks could properly be said to measure the various subsets of executive function ability. The initial approach to executive function was as an overall complex function (this could be compared to using the general language measures in investigating language ability; Milligan et al., 2007), but more recent work has aimed to fractionate it into simpler components (Brookshire, Levin, Song & Zhang, 2004; Lehto, 1996; Miyake, Friedman, Emerson, Witzki & Howerter, 2000).

Developmental studies investigating the relationship between executive function and ToM have found a relationship between executive function and ToM even when verbal ability was controlled for (Hughes & Ensor, 2005). The direction of the relationship between executive function and ToM has also been found to be stronger for early executive function performance predicting later false belief performance, rather than early ToM predicting later executive function performance (Hughes & Ensor, 2007).

Three of the more readily dissociated functional components of executive function are inhibitory control, working memory and planning, and all of these have been used in developmental studies (Carlson & Moses, 2001; Carlson et al., 2002; Carlson, et al., 2004; Hughes & Ensor, 2005; Hughes & Ensor, 2007) looking at the relationship between executive function and false belief understanding. From a conceptual viewpoint, looking at these three specific components of executive function is logical in terms of false belief understanding: inhibitory control may be required to inhibit self perspective (or one's own knowledge or belief) in order to process or understand another agent's belief. Working memory may be required to simultaneously process both one's own mental state and another's. ToM (and hence false belief understanding) has been implicated in the ability to plan future events by placing oneself in a hypothetical future scenario, in which one has different desires and beliefs to one's current state. In this situation one would use a separate (meta-) representation of one's own mental states, analogous to representing another agent's mental state as different from one's own current state. In this case the other agent's mental state is one's own future mental state. Therefore planning ability may be related to false belief performance (however the direction of this particular relationship is unclear).

A series of studies by Carlson and colleagues (Carlson & Moses, 2001; Carlson et al., 2002; Carlson, et al., 2004) investigated the components of executive function and their relationship to false belief performance using (mainly) individual difference studies. Their findings suggested that inhibitory control was related to false belief performance (and the relationship was stronger from early inhibitory control performance to later false belief performance than the reverse), and that working memory was also related to false belief performance, in the same casual direction. However, once inhibitory control was controlled for, working memory no longer had a significant relationship with false belief performance. Planning ability was initially related to false belief performance, but after controlling for age and language ability, it shared no unique variance with ToM performance (Carlson et al., 2004). This gives an idea of the issue of task specificity in executive function. It is difficult to design tasks that measure only one component of executive function, as the demands of tasks usually tap more than one component (inhibitory control and working memory are usually intertwined in some way). Work in the current thesis extends Carlson et al.'s solution of regressing out the effects of different components of executive function by using the statistical technique of structural equation modelling (Blunch, 2008; Kline, 2005).

In Carlson and Moses (2001), there was evidence for division within the construct of inhibitory control, beyond the initial division of executive function. They found that the specific type of inhibitory control task that was related to false belief performance was the 'conflict' inhibition tasks. A separate type of 'delay' inhibition task was also used, but was not found to be significantly related to false belief performance. An example of a conflict inhibition task is the Bear / Dragon task. Children were instructed to follow the instructions of the 'nice Bear' and to ignore the instructions of the 'naughty Dragon'. There seems to be an element of working memory required (to recall which puppet to follow instructions from, and which one to ignore), as well as inhibitory control to actually inhibit carrying out the Dragon's instructions. The conflict tasks therefore appeared to tap both inhibitory control and working memory resources. A delay task is typified by the gift delay task, in which children were told that the experimenter was going to wrap a present for them. Whilst the experimenter wrapped the present, the child was sat facing away from them, and was instructed not to look at the experimenter. Successfully not looking around at the experimenter (for 60 seconds) was counted as passing the task, and would seem to indicate the ability to inhibit impulsive responses. Delay inhibition tasks were therefore presumed to tap a relatively pure measure of control over impulsive responses.

The results indicated that working memory (measured using simplified backward digit span, backward word span, and counting and labelling measures), once controlled for by age and (or) intelligence no longer predicted false belief understanding. Conflict inhibition remained a significant predictor of false belief understanding when age and (or) intelligence was controlled for, and regression analyses suggested that conflict inhibition shared some unique variance with (and predictive power of) false belief understanding, whereas working memory did not. However, as conflict inhibition was not the pure measure of inhibitory control that delay inhibition was, the aspects of the tasks that are actually contributing to false belief understanding are unclear. Therefore, there is still an issue of task purity, as even though several tasks were used to establish both the conflict and delay inhibition factors, the conflict inhibition factor is still potentially separable into inhibitory and working memory components. Therefore there is evidence from developmental studies of three to four year olds for a connection between the ability to pass false belief tasks, and hence, demonstrate understanding of false beliefs, and language ability and specific executive function capabilities. Their exact contribution is not completely understood, although it seems that they are required (or are at least predictive of) the type of understanding required to pass standard false belief tasks. It is also unclear whether these relationships are necessary for the development of ToM, or whether they are a component in ToM throughout the lifespan.

Evidence from adults

There are different methodologies that have been used to investigate the relationship of both executive function and language ability with ToM. One method has been to look at adults with acquired brain lesions. The rationale for this approach is that if a function is necessary for ToM, then if that function is impaired in the patient there should be an impact on the patient's ToM performance. A similar way of investigating possible contributors to a complex task in typical adults is through the method of dual tasking (Phillips, Tunstall & Channon, 2007). In dual task studies the task of interest, usually a more complex task (for example the Wisconsin Card Sorting Task in Cinan & Tanör, 2002, or the non-verbal belief task in Newton & de Villiers, 2007), is designated as the primary task. The secondary task, which is undertaken at the same time as the primary task in the experimental conditions, is designed to tap a specific component that the primary task also requires. If the primary task does require this specific component, then participant performance in the dual task experimental condition should be worse than when the primary task is conducted alone. Performance in the secondary task should be collected together with performance in the primary task, in both cases when they are performed alone and together, to allow for comparisons to be made.

The role of language

The link between language ability and false belief understanding in children suggests that there may be a role for language in the development of ToM, but that does not entail that it is necessary in adults. There has been limited research on ToM in adults, but some studies have focused on the relation between language abilities and false belief understanding, studying either neurologically intact adults or adults with brain injury. These studies can provide evidence for the existence of a relationship between language and ToM in adults that would indicate whether language is critical to both the development of ToM and to ToM itself.

There have been only three clinical studies that have focused on the relationship between language and ToM in patients. All three only focused on the role of grammar in ToM, rather than any other aspect of language. Varley and Siegal (2000) studied patient S.A. who suffered a sub-dural emphysema resulting in a large lesion of the left hemisphere of the brain. He was left with both apraxia and aphasia, but his ability on an executive function task (Wisconsin Card Sorting Test, WCST) was not impaired. He also exhibited a severe impairment in sentence parsing and in sentence and verb comprehension. He was tested on a ToM task (‘changed container’ false-belief measures), as well as a causal reasoning task and the Wechsler Adult Intelligence Scale (WAIS) picture arrangement test. His performance on these tasks was well above chance, indicating that his ToM abilities were intact, as well as his abilities to reason causally. This was despite his severe impairment in grammatical ability.

Varley, Siegal and Want (2001) studied a patient, M.R., who suffered a left hemisphere cerebrovascular accident, resulting in severe aphasic difficulties and an inability to understand or produce language propositions. He was tested on the WCST to assess his executive function ability, that proved to be severely impaired (he failed to complete a single category in 128 trials). He was also tested on the WAIS picture arrangement test and a causal reasoning test, together with a picture-based ToM task. He exhibited above chance performance in all three of these tasks. These results are despite his severe impairment in both grammatical (language) ability and executive function ability.

The combined interpretation of these two studies would suggest that ToM ability does not rely on either language or executive function in adults. However, while more than one task was used to assess language ability, only one was used to assess executive function. The WCST may require executive functions that are not required for ToM that in M.R. may mean that he was impaired on those executive functions and not on those that ToM also requires. This will be returned to in the next section.

Apperly, Samson, Carroll, Hussain and Humphreys (2006) studied a patient, P.H., who suffered a left hemisphere stroke, affecting the left medial and superior temporal gyri, and the left inferior and middle frontal gyri. P.H. was assessed on a battery of language tasks, as well as several ToM measures. Language problems exhibited by P.H. included severe anomia, deep dyslexia, deep dysgraphia and difficulties in grammatical processing. He was able to use individual word meaning to interpret sentences for semantic plausibility, rather than by grammatical information. He did show impaired performance on differing types of embedded sentences similar to the embedded complement sentences said to be causally related to the development of false belief understanding in children: specifically for target relative clause sentences ("The woman pushed the man that opened the box") and adverbial clause sentences ("Before the woman pushed the man, the man opened the box")).

The pattern of results suggests that he was able to understand the embedded nature of the sentences, but his problem was more with the use of grammar to constrain the interpretation of the sentences. This would mean that if belief reasoning tasks, or reasoning tasks in general, rely on grammatically structured linguistic representations, P.H. would exhibit impaired performance. A series of ToM tasks were administered and P.H. passed the non-verbal measures of first-order false belief reasoning, and a non-verbal task that required second-order false belief reasoning. The first-order false belief reasoning task was a video-based version of the 'unexpected transfer' task (Samson, Apperly, Kathirgamanathan & Humphreys, 2005). The second-order false belief reasoning task required P.H. to infer that one character would wrongly believe that another character holds a false belief. He also passed a test of ToM semantics, and also story-based ToM tasks that did not require complex grammatical abilities. The only task condition that he did not score above chance on was the belief condition of a task that required grammatical understanding of an embedded clause. The task required P.H. to process a sentence and then choose the correct picture (from two) that matched the meaning of the sentence. There were two conditions, belief and reality, and the sentences were of the same format for both (‘he thinks there is a red ball in the box, but really there is a blue ball in the box). However, for the reality trials the choice was between two pictures of an actual ball in a box (either red or blue ball in a box on a table), whereas in the belief trials the pictures were of a blue or red ball in thought bubbles. For the reality trials P.H. only had to process the ‘really there is a…’ part of the sentence, and he performed above chance for these trials. For the belief trials, P.H. had to process the ‘he thinks there is…’, and in these trials he did not perform above chance. This suggests that grammar was only necessary to process the input to belief reasoning, but was not necessary for processing belief as such.

The evidence shows that these three agrammatic patients, with relatively spared lexical processing, were able to infer false beliefs (all could pass 1st order tasks, and P.H. could pass 2nd order belief reasoning tasks). This could suggest that the role of language is in the development of ToM. Nonetheless, whilst it is not an integral component, language is likely to be able to facilitate ToM in adults.

There have been different interpretations of this relationship, particularly as found in Newton and de Villiers’ (2007) study. They investigated the relationship between language (in general) and false belief performance. Their study utilised a dual-task methodology to investigate the effect of a rhythmic shadowing secondary task and a verbal shadowing secondary task on a non-verbal false belief task in adults and an equivalent true belief task. The data showed that the verbal shadowing impaired performance on false belief task, but rhythmic shadowing did not. Neither secondary task affected performance in the true belief task. This was taken to mean that the false belief task required language in order to pass it, and as that language ability was also required by the verbal shadowing task, performance in the false belief task was impaired. The fact that the primary false and true belief tasks were non-verbal lends more weight to this explanation, suggesting as it does that language is required even for tasks that do not actively employ language.

The performances of the participants in the secondary tasks themselves, however, were not reported. In dual-task studies, it is useful to examine the performance in both the primary (in this case the false and true belief tasks) and the secondary (rhythmic and verbal shadowing tasks) tasks. It is possible that the participants in the verbal shadowing task condition made errors only in the primary false belief task (but none in the secondary task), and that those in the rhythmic shadowing task condition made no errors in the primary task, but made errors in the secondary task instead. This gives an alternate picture of the results, in that participants may have focused on the verbal shadowing task rather than the false belief task in that particular condition, and that those in the other condition focused on the false belief task and not the rhythmic shadowing task. Whether participants chose to focus on one task rather than another is unclear, but does give a plausible alternate explanation when the data from the secondary tasks is not available. They may achieve this switching of focus using executive function. It is also possible that language may make specific demands on executive function.

These studies seem to show that the role of language in ToM is one that is critical to development, but that is not so in adults. Language ability may help ToM ability in adults, in terms of efficiency and accuracy, but the relationship between the two may not crucial.

The role of executive function

Studies have suggested that there is a link between certain executive functions and ToM in adults, as there are in children. Happé, Malhi and Checkley (2001) studied a patient P.B. after a standard surgical procedure to treat bipolar affective disorder. The surgical procedure produced two bi-lateral lesions, targeting neuronal connections between the mid-line thalamic nuclei and the orbito-frontal cortex. P.B. exhibited impaired performance on test materials requiring mental state attribution. These were a story task involving questions requiring an inference about the characters' thoughts and feelings, and also a single cartoon task in which P.B. had to explain why a cartoon was funny (half relied on what a character falsely thought or did not know hence required ToM, the rest did not). The final task was a cartoon pair task for which P.B. had to choose the humorous cartoon from a pair and explain why it was funny. Half the pairs required ToM to understand, half did not (each pair was identical except for the key humorous element). He also exhibited impaired executive functioning, specifically deficits in generativity, inhibition and set shifting. He was able to answer test materials that did not require mental state attribution, so there was a tentative link between executive function and ToM proposed. Similar impairments in ToM and in executive function were found by Channon and Crawford (2000) in patients with left anterior lesions, and Stone, Baron-Cohen and Knight (1998) found that patients with dorsolateral lesions exhibited improved performance on ToM tasks when external working memory aids were provided. The most specific relationship between executive function, in this case inhibitory control, and ToM was found by Samson, Apperly, Kathirgamanathan and Humphreys (2005). They studied a stroke patient, W.B.A., with right prefrontal and temporal damage, one of which resulted in poor inhibitory abilities. This exhibited itself, in terms of false belief performance, in difficulty in inhibiting his own perspective. However, the results suggest that he was still able to infer another agent's perspective, but that the inability to inhibit his own perspective led him to make egocentric errors.

This distinction was drawn through the use of low- and high- inhibition type false belief task, where the inhibitory control demands of the task was varied. W.B.A. was shown videos depicting two actors in a room. There were two small boxes in which there was a green block. The location of the block is unseen by W.B.A.. The female actor would be shown the boxes and the location of the green block by the male actor. At this point she would leave the room, and while she was out of the room, the man would move the block into the other box (again unseen by the participant). When the woman returned to the room, she would place an indicator on the box in which she thought the block would be. W.B.A. would then be asked to indicate where the block was. To successfully pass the task, the woman's false belief must be taken into account. In this low inhibition condition, W.B.A. did not have to inhibit his own belief. In the high inhibition version, the transfer of the block whilst the woman was out of the room was shown to the participant. When she returned, the participant was asked to indicate where she would look first for the block. At this point W.B.A. knew where the block really was, but also needed to understand that the woman had a false belief of the location of the block (that she would look in the initial location of the block. In order to correctly respond, W.B.A. needed to inhibit his own knowledge of the block location, in addition to inferring that the woman had a false belief. The degree of self-perspective inhibition was therefore higher for this (high inhibition) condition. W.B.A. was able to pass the low inhibitory control demand task, where he was simply required to infer her false belief, but failed when he was required to infer her belief and to inhibit his own.

However, there is evidence that impairment in executive function is not necessarily associated with decreased ToM performance (Channon, Sinclair, Waller, Healey & Robertson, 2004; Fine, Lumsden & Blair, 2001). Bird, Castelli, Malik, Frith and Husain (2004) studied a patient, G.T. After suffering a rare form of stroke that resulted in massive medial prefrontal cortex (PFC) damage, an area often associated with ToM (Frith & Frith, 2006), G.T. exhibited impaired performance on a variety of executive function tasks (the task battery included the Hayling Test, Stroop Test, the Trail Making Test, the Behavioural Test of the Dysexecutive Syndrome (BADS), Verbal fluency and the Modified Card Sorting Test). The pattern of results suggested impairments in planning and in memory. G.T. passed most ToM tasks despite her executive function impairment (these were the Picture sequences test, the strange stories task (an advanced test of ToM), the Violations of social norms test, the Faux Pas Test and an animations test). These results indicate that there is no relationship between executive function and ToM in adults. However, the impairments in executive functioning exhibited by G.T. may not be in those executive functions that are required for ToM. Memory may be required, in conjunction with inhibitory control, but planning has not been found to be related to ToM, at least in children (Carlson et al., 2004). Inhibitory control is the most commonly associated executive function with ToM, and on this G.T. was not as impaired as on other executive functions. This may account for her relatively normal performance on the ToM tasks. Another consideration is what aspects of executive function the ToM tasks used require, as used may not tap those specific executive functions.

German and Hehman (2006) also found a relationship between inhibition and accuracy and response times in the false belief task in older adults. This suggests that the relationship between executive function, and specifically inhibitory control, is present throughout the lifespan. This would seem to show that inhibitory control is necessary to be able to inhibit self perspective in adults. As the relationship between inhibition and false belief is also present in children, it would seem that inhibitory control is a necessary component for adults and children, and so is core to the development of ToM and to ToM in general.

There is recent evidence from ToM and social cognition dual task experiments that suggest that these abilities rely on domain general executive function abilities (rather than domain specific abilities that exist for ToM processing only). The evidence from these studies also suggests that there is a role for executive functions in ToM in adults (therefore beyond development only). Dual-task studies have focused on working memory contributions (McKinnon & Moscovitch, 2007) and inhibitory control (Bull, Phillips & Conway, 2008) to ToM.

McKinnon and Moscovitch (2007) tested adults on a story based ToM task in conjunction with a two-back task designed to tap working memory. The story task had two versions, a first-order ToM task and a second-order ToM task. The results showed significant impairments in both the first and second order ToM tasks in the dual-task condition, with performance in the second-order task also being significantly worse than in the first-order task. This suggests that working memory is required in belief reasoning in general, and to a greater extent in second-order than in first-order belief reasoning. The impaired performance in the two-back task in the dual-task condition supports this suggestion.

Bull et al. (2008) used the Reading the Mind in the Eyes test and an amended version of the Stories task (amended from an expressive production task to a multiple choice task), together with matched control tasks. The dual tasks used all had the basic requirement of listening to a string of numbers. The three tasks were an inhibition task (involving adding numbers and withholding the response to a certain total), a switching task (participants were randomly auditorily cued to switch between adding one or two to the number) and an updating task (participants had to add one to the number heard one previously). A version in which participants had to add five to each number was used as a control to match presentation and response, but with minimum executive load. Results showed an impairment in the Eyes task in the inhibition dual-task condition, suggesting that inhibition is required for that task. The Stories tasks (both experimental and control) were significantly impaired by all the dual-tasks, suggesting a general overlap of executive function and the Story task demands, not specifically with any one executive function component. Performance on the secondary tasks was not reported, so it is unknown if there were any differences between the secondary tasks.

Evidence therefore suggests a role for both executive function and language in the development of ToM, as far as it is the ability that is required to pass standard false belief tasks (at around ages three – four). Prior to this, there is evidence showing that infants are able to predict behaviours of other agents based on their beliefs being true or false. Whether this is the same ToM ability that is used to pass the standard false belief tasks but manifest at an earlier developmental stage, or whether it is a separate component of an overall conceptual ToM ability (of which the ability to pass the standard false belief tasks is another component) is unclear. However, the available evidence suggests that whilst executive function and language are both used in adults' ToM processes, only the need for executive function has been demonstrated as strictly necessary. Language ability, primarily in the case of grammar, facilitates ToM performance in adults, but may not be integral to it. The data are consistent with the view that some aspects of ToM are dependent on executive function and language. However, the infant data does not fit with this view, as those studies show that infants possess some perspective taking abilities without having recourse to language or executive function abilities. Therefore there could be at least two potential components of ToM. These could be characterised respectively as a simple, cognitively efficient ability (infant perspective taking and implicit belief understanding) and a more flexible, cognitively demanding ability (the ability shown to pass standard false belief tasks, requiring development of both executive function and language, but needing only the former and being facilitated by the latter). Data from animal studies suggest that some animals also exhibit a perspective taking ability with limited executive function ability and without language ability. This may provide converging evidence for the existence of a cognitively efficient, inflexible ToM system that is responsible for perspective taking (at least). It is also possible that typical false belief tasks can not be passed by infants or animals only because the tasks have additional task demands that require executive function and language ability that they do not have. This view allows infants and animals to have an understanding of false belief (that can not be demonstrated using typical false belief tasks).

Evidence from animal studies

Studies from the area of animal cognition provide some converging evidence for the existence of a relatively simple perspective taking ability, analogous to what is found in human infants. There are two main views on the evidence from this area, one that suggests that what is shown (primarily by apes) is at some level, perspective taking abilities (Tomasello, Call & Hare, 2003), and one that claims that the evidence can be explained by behavioural rules, and that it is our own ToM that makes us interpret other species' behaviour as showing evidence of ToM (Povinelli & Vonk, 2003).

Tomasello, Carpenter, Call, Behne and Moll (2005) have suggested that primates have a basic form of ToM, insomuch as they are able to understand others as animate, goal-directed and having intentions. The distinction made between this and the ToM present in children (and hence adults) is based on humans having a unique motivation to share emotions, experiences and activities with other agents. This cooperative motivation is said to be the driving force behind the 'shared intentionality' of humans that results in what is seen as human cognition, incorporating ToM. This early recognition of others as goal-directed, animate and intentional agents may explain why children can succeed in perspective taking tasks at 14 months (Sodian et al., 2007), well before ToM is fully developed, and also why apes are also able to succeed in perspective taking tasks (Hare, Call & Tomasello, 2001), whilst both are unable to pass ToM tasks.

The cooperative nature of humans is said to be the basis for the development of the skills that enable children to then pass ToM tasks sometime after four years of age. Primates have a more competitive social arena, so the spur to develop understanding of other mental states is not present or indeed needed as it will not bestow any advantage. As noted, some researchers have suggested that primates do not have a ToM, and that evidence for ToM in primates (in terms of actions and behaviours in experimental settings) can be explained by behavioural abstraction (Povinelli & Vonk, 2003). The suggestion is also that as humans have a ToM, they are predisposed to interpret others' actions in terms of ToM – this applies to humans (which works well) but can also apply to interpreting the behaviours and actions of primates, which may be a fallacy.

The emphasis on the integral role of co-operation and shared intentionality in the developed ToM present in children and adults could be seen as an emphasis on a type of behaviour that relies on language and executive function. Without language and executive function, the specificities of shared intentionality may not be possible: simple perspective taking may be automatic and hence not require any executive function (particularly inhibitory control), but the more complex ToM abilities that are held to be present in children and adults seem to require language and executive function, and evidence from developmental studies bear this out (though adult studies seem to suggest that language ability acts as a facilitator, whilst executive function is required). The explanations of the abilities shown by infants and apes do seem to point to a potentially common ability to understand at least the differing perspectives taken by other agents. The understanding of mental states as such may also be a part of this ability, but a more conservative and perhaps more realistic interpretation of the data would exclude this (Penn & Povinelli, 2007; Ruffman & Perner, 2005). This gives some converging evidence for the presence of a cognitively efficient ToM ability (that does not rely on executive function and / or language) that allows infants and apes to pass simple perspective taking tasks, and at the very least show some understanding of agents having different perspective to their own. Again, an alternative explanation is that full false belief understanding (or ToM) is present in animals (and infants), but that this can not be demonstrated using typical ToM tasks because of their requirements for executive function and language abilities.

Evidence from neuroscience

The two main areas of evidence within this field are from neuropsychological studies, highlighting regions of the brain that are necessary for ToM, and from fMRI imaging studies that highlight all the regions that may be involved.

A detailed explanation of the areas associated with ToM is given by Siegal and Varley (2002). In their review of imaging and lesion studies they argue that the core components of ToM are centred in the medial temporal lobe-amygdala area, orbitofrontal cortex and superior frontal gyrus. These areas are associated with i) inhibition, working memory and empathy ii) empathic ToM, emotional perspective taking (and the dissociation between ToM reasoning tasks and other closely related tasks) iii) frontal eye field and attention respectively. They suggest that the amygdala system and its interconnections with the prefrontal and temporal lobe structures could be responsible for a range of socio-cognitive behaviours, including lower-level behaviours (such as determining emotional significance). Together with what are described as co-opted systems such as the right-hemisphere non-frontal area (specifically the superior temporal sulcus (STS) for detecting motion of animate objects, and hence inferring intentions from actions, and the right inferior parietal cortex, precuneus and somatosensory cortex in distinguishing perspectives of self from others), the frontal lobes (executive functioning), and the language centres of the brain (enables propositional reasoning about mental states) enable human ToM as we know it. This posits a link between executive function and language and ToM in adults, much as there is a link between them in children.

A more recent imaging review by Frith and Frith (2006) has associated the posterior end of the STS and the temporoparietal junction (TPJ) with perspective taking, in that these areas are associated with eye-movement observation (where someone is looking) and also representing the world from different visual perspectives. The temporal poles are associated with knowledge about the world, in terms of experience of how to behave in certain situations, how particular situations can affect particular people that we know, amongst other knowledge gained throughout our life. This knowledge is used to aid mentalising. The medial prefrontal cortex (PFC) alone is associated with thinking about the mental states of others and the mental states of the self.

It is possible that functions of the PFC can be segregated into different areas, as evidence is present that the more ventral regions are associated with emotions of others and the self, while the more dorsal regions are associated with monitoring actions of the self and others (more cognitive). The region between these areas, the anterior rostral MFC, is activated when we notice someone is going to communicate with us. The activation may be in this region as it is adjacent to the two regions dealing with emotion and action, and is so able to combine and process those two aspects.

The review by Frith and Frith (2006) posits no direct links between executive function and ToM, though it shows how there is more than one area associated with ToM. An interpretation of this could be that ToM could be separable into more than one system, potentially with different underlying components or demands.

Other patient studies that have investigated ToM impairments and in particular executive functioning in (specifically with frontal lobe lesions) have found varied results. Rowe, Bullock, Polkey and Morris (2001) found that their sample of patients with unilateral frontal lobe lesions (left and right) had common deficits in ToM tasks, and also in executive function tasks. However, they did not find any causal relationship between the two sets of tasks. Their argument for the common finding of a combination of ToM deficits and executive function deficit is due to the close proximity (or same area) of the brain regions associated with both aspects. Therefore it is possible that people can have deficits in ToM, deficits in ToM and executive function, or deficits in executive function, all of which are independent of each other. However, all this may mean is that there are potentially different brain areas that are independently responsible for executive function and ToM.

Other studies that have investigated the areas of the brain associated with ToM include Samson, Apperly, Chiavarino and Humphreys (2004) (who identified the left TPJ as necessary for reasoning about others’ beliefs), Apperly, Samson, Chiavarino and Humphreys (2004), and Stuss and Anderson (2004) (who proposed a hierarchical development of essential brain areas, mostly focused on the frontal lobes). Functions associated with these brain regions could result in further evidence on the functional basis of ToM.

Perspective taking studies in adults (Perner, Aichhorn, Kronbichler, Staffen & Ladurner, 2006), and imaging studies using different story conditions (Saxe & Powell, 2006) have investigated the possibility of there being, respectively, separate areas of the brain associated with perspective taking and an early developing ToM component. Saxe and Powell (2006) gave participants stories that fell into three separate categories, and monitored their brain activity whilst they read them. Appearance stories described the physical and social characteristics of the protagonist. No subjective or mental states were described explicitly in this condition. Bodily-sensation stories described the protagonist's subjective feelings, but did not describe explicit mental states, only internal experiences. This type of feeling or state was deemed least likely to be interpreted using a rich representation. The final category was that of thoughts stories, in which the participants were required to represent the protagonists' beliefs (and thoughts). This category was thought to require the classic ToM abilities that emerge around four to six years of age (comparable to the cognitively demanding and flexible component).

The results from the study show a different area of activation (the supramarginal gyrus, SMG) for the bodily-sensation stories than for the appearance and thoughts stories, but also different areas of activation (right and left TPJ and posterior cingulate) for the thoughts stories than for the appearance and bodily-sensation stories. The medial prefrontal cortex (MPFC) was activated in all three story categories. The results were interpreted as showing that the right TPJ and left TPJ and posterior cingulate are required for representing and interpreting a protagonist's thoughts and beliefs, whilst the SMG may be (one) of the areas responsible for the attribution of subjective physical feelings. This area has also been associated with the attributions of basic emotional states. As the MPFC was activated in all conditions, it may have a general role in representation of relevant social and / or emotional information of another agent. The upshot of this pattern of results is again a distinction between an early developing theory component (involving the SMG, and used in the attribution of basic emotional states and also in perspective taking) and a later developing ToM (involving the TPJ and posterior cingulate, and used in representing thoughts and beliefs of another agent). The MPFC is said to be used in a broad role of the representation of relevant social and emotional information, present in both early and late developing ToM aspects. This study also uses the idea of two components of ToM, but the areas associated with these components differ from Perner et al. (2006).

Perner et al. (2006) used several conditions of a perspective taking task. This task consisted of six conditions, in which five included a short red block and a tall black stick. Of these five conditions, four included a human figure and one included a camera. The four human figure conditions were presented as a scene with a sentence above them. Participants were required to verify if the sentence matched the scene as shown (two conditions with different positioning of the block and stick), or if the sentence matched the scene as seen by the human figure (two conditions again with different positions of the block and stick). In the camera condition participants were asked to judge whether a picture shown above the scene could have been taken by the camera in its position in the scene. In the final condition participants were asked to judge whether the two groups of objects present in the scene were composed of the same or different kind of objects. The results showed that the medial prefrontal area of the brain, associated with activation during ToM tasks (Frith & Frith, 2003), was not activated in this task. This is even though the tasks required level two perspective taking. However another area of the brain associated with ToM tasks, in particular false belief tasks, the STS / TPJ area (Saxe & Kanwisher, 2003), was activated. As false belief tasks and the conditions in the Perner et al. study both require the ability to represent belief as perspective, hence making a conceptual link with visual-perspective taking, and both had similar areas of activation, the results were said to indicate that the STS/TPJ area is required for taking perspectives and predicting behaviour, whilst the medial prefrontal area is required for making behavioural predictions and the wider consequences of that behaviour, especially the emotional consequences.

However, this is a general issue with imaging studies in the ToM literature, with different studies finding different areas of activation, sometimes attributing these activations to different potential processes and components. Several areas are repeatedly found to be activated in ToM tasks, including the MPFC, STS and temporal poles (Frith & Frith, 2003), but a definite interpretation of the roles of these areas is still under debate. Some of this uncertainty is due to differing experimental procedures, but another reason is the varied types of task that are used to tap or measure ostensibly the same process, ToM. Imaging studies often only require participants to read stories or a series of images in order to see what areas are activated whilst this occurs. Studies on typical samples, both developmental and adult, use stories, images, and videos, which will have different incidental demands on them, and would reasonably require different resources to accurately process them. Another issue is what other processes the areas activated by ToM tasks are responsible for, or have been associated with. These could include aspects of executive function. Therefore it is more realistic to attempt to constrain the processes that a task is designed to measure.

Two processes of Theory of Mind : Evidence from adults

A model that incorporates the possibility of there being two systems available for ToM could explain the discrepancy between task performances shown in these studies when executive function impairment is not associated with ToM impairment: a cognitively efficient (but perhaps rather inflexible) system would arguably be unaffected by executive function impairment, and this may be enough to pass simple ToM tasks (such as those used with infants, and with some brain-injured patients). This system may have the potential to adapt to compensate for the cognitively flexible system that may have been impaired by the executive function impairment.

The separation of ToM into two potential components by Perner et al. (2006) mirrors, in some respects, the division between the two proposed components of the two-system approach of a cognitively efficient inflexible component and a cognitively demanding flexible component. The two-system approach does not explicitly take into account the particular consequences of behavioural predictions, but the emphasis on the difference in complexity between the two components suggested by Perner et al. and the two components in the two-system approach is similar.

Flexible and cognitively demanding system

There have been studies focusing on ToM abilities in typical adults. Keysar et al. (2003) used a communication game experiment to investigate adults' abilities to follow the directions of an instructor to move objects around a grid. The basic premise was that some objects were visible to both the instructor and the participant, and some were only visible to the participant (as they were hidden in a bag by the participant without the director's knowledge). In critical trials, the instructor's directions could refer to a mutually-visible item or to the object hidden in the bag.

Results showed that participants both reliably looked at the object only known to them as a possible choice (the non mutually-visible object) and also made errors by selecting that object to move. A second experiment used a false belief manipulation, where after the object (a cassette tape) was hidden by the participant without the director's knowledge, the participant and the director were shown a picture of what ostensibly was in the bag. This picture was of a different object to the contents of the bag, so the participant should realise that the director now held a false belief about the contents of the bag. In the critical trials, where the referent of the instruction could be the item in the bag or a mutually visible item, participants still tended to look at the bag as a possible choice, and also chose the bag as the item to move.

The pattern of errors from this particular experiment and the other experiments from the same study (Apperly, Carroll, Samson, Qureshi, Humphreys, & Moffatt (in submission)) are said to show that participants do not have difficulty in taking the instructor's perspective or in switching perspective, but that the difficulty arises from the potential limited capacity for being able to infer and hold in mind the instructor's perspective and the use of this to then respond accurately. These abilities are said to relate to generic executive functions, and, as covered, in conceptual terms inhibitory control and working memory would likely be the best candidates for the specific executive functions associated with ToM. The association of this task with executive function, together with the high error rate (~ 25% – 50%), and long reaction times (~ 2000 ms) would associate it with the second component of the proposed two-system model ToM, in that it is cognitively demanding (greater requirement for executive function), requires flexibility and is complex, and results in participants being more prone to errors. There is evidence to suggest that children are able to pass a simplified version of this task (Nadig & Sedivy, 2002), but the grids used in that study were smaller with fewer items, so the associated executive function demands would have been appreciably less.

Both of these experiments indicate that adult participants make mistakes in utilising their ToM abilities, by consistently not taking the instructors perspective or beliefs into account when following their instructions to move an object. A reason for this failure to take another's belief or perspective into account could be the difficulty in discounting the self perspective, or the tendency towards egocentrism (Epley, Keysar, van Boven & Gilovich, 2004a; Epley, Morewedge & Keysar, 2004b; Wu & Keysar, 2007).

A review of evidence and theory relating to egocentrism (Royzman, Cassidy & Baron, 2003) suggested that there is a tendency in both children and adults towards egocentrism (termed in the review as epistemic egocentrism), and that this bias may be mediated by inhibitory control (executive function). In addition to the studies already mentioned in this introduction, there are studies on older adults that have found impaired (compared to younger controls) performance in ToM tasks (Maylor, Moulson, Muncer & Taylor, 2002) but this impairment was present when executive function tasks were controlled for. Incidental task difficulty is an issue here, as well as task purity in terms of whether the executive tasks are measuring what they are meant to be measuring. This also applies to the demands of the ToM tasks used.

Studies have found impaired performance in an older adult sample (again compared to younger controls) in executive function tasks (Zelazo et al., 2004). German and Hehman (2006) found impaired performance by older adults in a standard false belief task, but not in an equivalent true belief task. As mentioned, they also found a relationship between inhibition and accuracy and response times in the false belief task. The relationship between executive function (specifically inhibitory control) is hence likely to be present throughout the lifespan, as the general impairment in executive function (Maylor et al., 2002; Zelazo et al., 2004) has an effect on the performance of older adults in ToM tasks, specifically in those requiring representation of false beliefs, that conceptually requires the setting aside, or inhibition, of the self perspective.

Egocentrism has been shown to be present in both children and adults (Epley et al, 2004b). The results from the study of Epley et al. (2004b), and from the study of Epley et al. (2004a) shows that both children and adults tend to start with an egocentric interpretation, but differ in how quickly they can correct this. The participants in the latter study serially adjusted their initial egocentric interpretation to the most plausible interpretation (not necessarily the correct interpretation), and this adjustment was mediated by how different the alternate perspective was from their own (further away resulted in a slower adjustment, by time pressure (increased bias under increased time pressure), and by accuracy incentives (increased accuracy of adjustments). The ability to serially adjust the initial egocentric representation to a more plausible representation is more developed, faster and efficient in adults, and this is said to be why adults do not show as much egocentric bias as children. This ability could be mediated by inhibitory control, as to move away from the initial egocentric intrusion may require inhibition of that representation (or at least some level of interference control).

A study by Apperly, Back, Samson and France (2008) investigated the cost of thinking about false beliefs. In a non-inferential ToM task, where participants did not need to infer a false belief (they were told what the character in the story believed), a cost in terms of efficiency (in both reaction time and error rates) was shown when the character had a false belief as compared to when they had a true belief. This was put down to the fact that the content of the false belief conflicted with the reality (which was not the case in the true belief trial). The ability to deal with this potential interference between belief and reality, even when there is no inference required, would seem to plausibly require at least some aspect of executive function, and more specifically inhibitory control.

Another study by Apperly, Riggs, Simpson, Chiavarino and Samson (2006) found that participants took significantly longer to respond to unexpected probes requiring them to respond concerning where another person thought an object was (not where it actually was) seemingly indicating that this type of inference, using belief reasoning, is actively carried out only when required. It follows that belief reasoning is not automatic. This explanation was supported in other conditions from the same study in which participants were instructed to follow the actor’s belief throughout the task. This resulted in no differences in the response time to probes about the actor’s belief of where the object was (belief probes) and where the object actually was (reality probes). If this is correct, then this type of belief reasoning, that is similar to the requirements needed for standard false belief tasks, may well require inhibitory control (to inhibit self perspective), and be flexible and more prone to errors (as seen in the study by Keysar et al. (2003)). This may be equated to the proposed ToM component that is required to pass the standard false belief task, which incorporates executive function and so is cognitively demanding but flexible. This might be contrasted to a ToM component that is cognitively efficient (less requirement for executive function), but may be less flexible (following from the current analyses, efficiency comes at the cost of flexibility), that is used by infants to pass perspective taking tasks and simple mental state understanding paradigms.

Efficient but inflexible system

There is some evidence for an efficient and inflexible system or component that can process perspectives quickly and accurately. Samson, Apperly, Braithwaite, Andrews and Bodley Scott (submitted) designed a task in which the participant was shown a room containing an avatar and circles (that could be present or not) on opposite walls. The information in their perspective (how many circles they could see) could either be consistent with what the avatar could see or inconsistent (the circles were on the walls in front and behind the avatar, so it could only see one wall where circles could be present at a time). Participants were asked to judge either their own perspective or that of the avatar at the end of each trial by verifying a number of circles that either they or the avatar could see. Results showed that participants processed the perspectives faster when they were consistent. When they were inconsistent, the response time was significantly longer, indicating some interference from the alternate perspective. This was true when they were asked to look from the avatar’s perspective, with interference from their perspective, which was expected. There was also, however, interference from the avatar perspective when they were asked to focus on their own perspective, suggesting that they were processing the avatar’s perspective even when they did not need to do so. This would imply that this processing of another’s perspective was a (at least relatively) automatic process that by definition is inflexible. The proportion of errors in the task was very low (~ 8.00%), and the reaction times were relatively fast (~ 650 ms), compared to those from the Keysar task, which is a pattern of results that would be associated to a fast, cognitively efficient, inflexible component, that is less prone to errors (due to a lack of complexity of the component). This is in contrast to the type of flexible and more error-prone processing that seems to be used in more standard ToM task (such as Keysar et al., 2003).

The evidence suggests the possibility of two systems for ToM, with data from developmental, adult, clinical and non-human animal research converging towards that premise. There is also evidence for similar two-system approaches in cognition from different areas of psychology. Feigenson, Dehaene and Spelke (2004) reviewed existing literature in the field of number cognition, and related the results shown to the possibility of there being two separate systems available. Results from studies investigating children's abilities with groups of objects or items were characterised by apparently arbitrary limitations, argued to be attributable to a system for number cognition used for approximate representations of numerical magnitude (Lipton & Spelke, 2003). Studies investigating precise representations of distinct items found similar arbitrary limitations in terms of the absolute numbers of the individual items (Feigenson, Carey & Hauser, 2002). This difference in the results (size of the ratio of the groups in the group dictating distinctions between groups of objects, but the absolute number of items dictating distinctions between distinct items) is best typified as representative of two different systems. The approximate number system is also present in adults and older children, where discrimination between groups of items also exhibit ratio-dependent restrictions and is also robust across different modalities (Temple & Posner, 1998; Trick & Pylyshyn, 1994). Study on non-human animals have shown a similar pattern of results in approximate number and discrete number distinctions, potentially supporting this two-system approach as present across species and across differing modalities, all characterised by the same set of arbitrary limitations. Other areas of psychology, such as that of general reasoning and social cognition (Todorov, Harris & Fiske, 2006; Frith & de Vignemont, 2005) have also used a two-system approach to resolve seemingly anomalous sets of results.

The investigation of a potential two-system approach to ToM means that the type of perspective taking task that infants have been shown to pass in recent literature (Onisihi & Baillargeon, 2005; Sodian et al., 2007) should also inform what type of task should be used. If this type of task is said to typify the fast, inflexible and cognitively efficient component (it does not require executive function), then there needs to be a task that exemplifies the other component that is suggested to require executive function and is more complex and flexible, but more error-prone.

Current study

The principal aim of the current study was to conduct the first large-scale individual differences study of ToM and executive function in adults. The literature gives many possible avenues of research. The chosen path was to use two ToM tasks that seemed similar in terms of conceptual demands on ToM, but appeared to differ in terms of response patterns (error rate and reaction times). The task that was used to tap the proposed fast, inflexible and cognitively efficient component of ToM was the perspective taking task (experiment 1a) from the study of Samson et al. (submitted), as detailed earlier. The task chosen to tap the proposed flexible, cognitively demanding component of ToM was an adaptation of the original task developed by Keysar et al. (2003). This version was developed for use in a study by Apperly et al. (in submission). The specific task to be used from this study was the ignorant instructor condition of Experiment 3 (also described earlier).

Different predictions follow for the proposed two-system approach as compared to the established one-system approach. A one-system approach would suggest that the two tasks will correlate, and any differences between them are due to differences in task difficulty. The visual perspective task involves taking the perspective of another (in the avatar focusing trials), maintenance of that perspective and the information contained, and resistance to any interference from (self or avatar) alternate perspectives. The Keysar task also involves these task demands. In addition, in the Keysar task the participant also needs to use that information in order to solve a problem by integrating it with the instructions of the instructor. The number of items needed to be held in mind is also greater for the Keysar task. However, as the majority of the task demands are similar (perspective taking, the use of the information gained from taking that perspective, and dealing with any interference between perspectives) the suggestion is that the two tasks will correlate. Executive function may or may not be required for the above processes.

The two-system approach would not necessarily predict a correlation between the two tasks, as they are posited to tap two separate components of ToM. There may also be differing requirements for executive function in the two tasks.

Based on the literature, inhibitory control was focused on, as this has been shown to have the most specific involvement with ToM. However, it is likely that other executive functions are also involved. Developmental literature suggests that working memory may be a candidate for a role in ToM (Carlson & Moses, 2001). Working memory may be required by the Keysar task to hold in mind all of the potential referents in a trial, whereas it is unlikely to be needed for that role in the visual perspective task. Executive function may also be required for the integration of instructions and information from perspective in the Keysar task. Inhibitory control could conceptually be needed to take another alternate perspective, through having to inhibit the self perspective, and this requirement should be common to both tasks. Conflict resolution between the self and instructor or avatar perspectives is also common to both tasks, and may also require inhibition.

It is possible that the executive function demands associated with the two tasks may differ based on their relative requirements (Stuss & Alexander, 2007). Therefore due to the possibly different demands of the two ToM tasks, there may be different executive functions that can contribute to them. This interpretation suggests that even though the same underlying system is used in both tasks, the results could show no relationship because of their recruitment of different executive functions due to their different task demands.

2. Executive Function and task selection for individual differences study

Task Selection

The literature reviewed in Chapter 1 suggests that there is a role for executive function in theory of mind. Evidence has been shown for a relationship between them in children (Carlson & Moses, 2001; Carlson et al., 2002; Carlson et al., 2004), and there is also evidence for the relationship in adults, from studies on clinical patients (Channon & Crawford, 2000; Samson et al., 2005; Stone et al., 1998) and also on typical adults (Bull et al., 2008; McKinnon & Moscovitch, 2007). However, this evidence is limited by the type of tasks used, as they may measure more than one executive function. The aim of the current study was to establish reliable estimates of valid executive functions, which could then be used to ascertain any potential relationships between executive function and ToM. Most of the studies that investigate executive function in relation to another construct use a single task as a measure of a given executive function. One of the issues to consider in executive function research, and also in ToM studies, is what precisely a task may be measuring. Executive function is an overarching term for a collection of functions, and the older tasks used to measure it are now understood to actually measure a large and varied number of these functions. These functions include planning, attention, inhibition, and working memory used singly and in combination in order to plan and achieve goal-directed behaviour (Norman & Shallice, 1980; Shallice, 1982).

Tasks that have been used to measure executive function include the Tower of Hanoi (ToH) task and the Stroop task. These tasks require a combination of processes. The ToH task requires planning ability in the movement of the discs whilst anticipating possible future moves. It may also require working memory to maintain rules, instructions and strategies. The Stroop task may also require working memory, and also requires inhibition of the dominant response of responding to the semantic information of the words presented. These tasks therefore do not measure any single process of executive function.

Early models of higher cognitive systems, such as the initial working memory model of Baddeley and Hitch (1974), often contained a central executive component which was responsible for the regulation and control of cognitive processes. This component is analogous to executive function, and shows that the initial concept of executive function was unitary. Therefore one of the issues arising from attempting to define executive function was to what extent it was a unitary mechanism (or ability) or a set of separable processes. Therefore the processes that are grouped under the general executive function umbrella have been more recently studied in terms whether they are dissociable or are part of a more unitary construct.

Fractionation of executive function

Although some studies have found evidence for there being a unitary ability or mechanism underlying the various components (Duncan, Emslie, Williams, Johnson & Freer, 1996), there is evidence for the potential fractionation of executive function abilities. This has come from studies on clinical populations, where participants have shown normal performance on well defined cognitive tasks (Damasio, 1994; Shallice & Burgess, 1991), but have shown impaired performance on tasks which are ostensibly more complex and less well defined, such as the aforementioned ToH task and the Wisconsin Card Sorting Test (WCST). Differing patterns of data from different clinical studies have shown that participants are often impaired in one type of task and not another, but then other participants show the opposite impairment (Godefroy, Cabaret, Petit-Chenal, Pruvo, & Rousseaux, 1999). Such double dissociations are taken to indicate that there are different components of executive function that are tapped by different tasks.

It is generally accepted now that tasks that have been used to measure a particular process of executive function can tap more than one of these processes. It is therefore difficult to use one task to measure a single executive function, as that task may measure different executive functions in addition to, or instead of, the proposed one. It is also possible that an executive function that one task is measuring may be more complex than first supposed, leading to a task that again taps more than one executive function. For example, inhibition was initially treated as a single construct. Many classic inhibition tasks, such as the Stroop task (Jaensch, 1929; Stroop, 1935), have been said to tap what are now considered differing types of inhibition. The task is to respond to the words shown on a page by giving the colour of the ink they are printed in. In the interference or experimental condition, the words are also colour words (for example, the word ‘red’ will be printed in blue ink – the correct response is ‘blue’). The semantic information of the word (red) conflicts with the visual colour (blue) of the word. Dealing with the conflict between the different sets of information taps cognitive inhibition, insomuch as it is required for monitoring that conflict (Lansbergen, van Hell & Kenemans, 2007). Response inhibition may also be required (Young, Bramham, Tyson & Morris, 2006) in order to inhibit any response to the semantic information given (red). It is possible that working memory is also required to retain the instructions for doing the task. In this way a task that was said to measure inhibition may require response inhibition, cognitive inhibition and working memory, meaning that tasks are never a pure measure of a single construct.

Developmental evidence

Executive function has also been studied in children (see Hughes, 2002), and there is evidence from developmental studies for separable simple executive functions. Areas proposed include cognitive flexibility (comprising working memory, divided attention, conceptual transfer and feedback utilisation), attentional control (inhibition, self-monitoring, self-regulation and selective attention), goal setting (initiative, conceptual reasoning, planning and strategic organisation), and information processing (efficiency, fluency and speed of processing) (Anderson, 2002). Other studies have found independent abilities in inhibitory control and working memory, that can be used in conjunction (Beveridge, 2002), whereas others have found interactions between them, albeit at an earlier age (Perner & Lang, 1999). The implication here is again that there are simple executive functions that may be used in conjunction with one another in more complex tasks.

Individual differences studies

An alternative to patient studies, that can be tested using typical participants, is an individual differences approach. This can be used to establish which executive functions are distinct from one another. This approach can also show what executive functions are tapped by particular tasks. This approach has been used on a variety of a samples: typical young adults (Lehto, 1996) and elderly adults (Rabbitt & Lowe, 2000; Robbins, James, Owen, Sahakian, Lawrence, McInnes & Rabbitt, 1998), clinical populations of adults (Burgess, 1997; Burgess, Alderman, Evans, Emslie, & Wilson, 1998; Duncan, Johnson, Swales & Freer, 1997), and children with neurocognitive pathologies (Levin, Fletcher, Kufera, Harward, Lilly, Mendelsohn, Bruce, & Eisenberg, 1996; Schachar, Tannock, & Logan, 1993; Welsh, Pennington, & Groisser, 1991). Participants are given a series of (executive function) tasks, and the performances on the different tasks are compared using correlation-regression analyses, and sometimes exploratory factor analyses (EFA). A common finding from these studies is that the inter-correlations between the executive function tasks is often low ($r = 0.4$ or less) and are often non-significant. EFA results also tend to show executive function tasks loading on many different factors (Miyake, Friedman, Emerson, Witzki & Howerter, 2000). The low correlations indicate that though there may be some association between the various processes, the main processes that these tasks tap can be treated as separate from one another. This gives support to the view that simple executive function constructs can be dissociated from one another.

An issue with using single measures in studies of executive function is that a low score in a task that is proposed to measure a given executive function does not necessarily mean there is an weakness in that single executive function, for that would assume that the task is a pure measure of (that particular) executive function (Miyake & Shah, 1999). The exact nature of the executive function impairment shown by a low score in a single executive function task is therefore difficult to ascertain. This is an issue of task impurity (Burgess, 1997; Phillips, 1997), and also means that low inter-correlations and the loading on multiple factors of executive function tasks do not inevitably mean that those tasks are all measuring different functions. As noted, many classic executive function tasks (such as the Stroop task, ToH and WCST) do tap many different potential components of executive function.

One way of dealing with the problem of complex tasks is to use simple, more constrained tasks that can arguably be said to tap only one executive function component. A number of studies have utilised this approach to some degree (Stuss & Alexander, 2007) but even a task that has been constrained to ostensibly measure only one executive function component may still require other resources. There will also always be incidental task demands that could affect task performance. This method does not allow for a task to have any error associated with it – the assumption is that it is a perfect measure.

Stuss and Alexander (2007) used an alternative way of dealing with measurement error, by using a series of tasks that varied in complexity. They systematically tested patients with various lesions on these tasks, starting with the simplest that ostensibly tapped only single processes. The single processes affected by particular lesions could then be seen by the performance on these simple tasks. They then tested the patients on progressively more complex tasks (the initial tasks were progressively more complex versions of the same task, but the final tasks were established, complex, executive function tasks that tapped more than one process). The more complex processes affected by particular lesions could be seen by the performance on these complex tasks, but this information was informed by the pattern of performance in single processes. Therefore the contribution of single processes and incidental task demands (measurement error) to the more complex tasks can be estimated. This allows the contribution of measurement error to the complex tasks to be taken into account. The pattern of performance in the tasks tapping single and complex processes for the different lesions of the patients also showed the possible location of both these processes and the network of processes (and which processes were likely to be involved in which network). As noted in Chapter 1, another implication of this study is that the executive functions underlying a given task may differ depending on the difficulty of that task. A task that has additional demands may require different executive functions than a more parsimonious version of the same task.

Latent variable analyses

An alternate way to deal with the task impurity issue is to use latent variable analyses. This allows what is statistically common across multiple tasks to be 'extracted' to form a purer factor of the component of interest (Miyake et al., 2000). These latent variables can represent theoretical constructs about characteristics of persons (such as executive function) (Kline, 2005). Therefore when studying executive function, several tasks that tap the component of interest would be used to measure a latent variable that represents that component. These tasks are defined as indicators that allow the measurement of the unobserved latent variable (it is not directly measured). This allows that variable to be a pure measure of the construct as it does not have any measurement error associated with it. The tasks, which are impure measures of that construct, have associated error terms that represent all the variance that is not related to the executive function component. The relationships of the tasks with the latent variable therefore creates a pure factor.

Miyake et al. (2000) used this individual differences approach to examine which executive function components (from mental set shifting, information updating and monitoring, and the inhibition of prepotent responses) were tapped by the ToH task, WCST, random number generation (RNG), operation span, and dual tasking (all frequently used executive tasks).

The components were created by testing participants on a battery of executive function tasks posited to measure the often cited executive functions listed above. Participants were also tested on complex executive tasks (ToH, WCST and RNG). A model consisting of three latent variables fitted the data. These three latent variables were interpreted as representing shifting, updating and inhibition by the authors. The findings show that the ToH task tapped the inhibition of prepotent response factor; the WCST tapped the mental set shifting factor; RNG tapped both the inhibition and updating factor; and operation span tapped the updating factor (the dual task tapped none of the factors). The three factors were correlated, but not strongly, pointing towards their separability. This indicates that these three latent constructs are separable components within the umbrella term of executive function, but that there is still some communality amongst them (otherwise there would be no correlations). The study also shows that the classic executive tasks do require more than one of the simple executive functions identified by the battery of tasks.

Inhibitory control

Inhibition is the executive function that is the main focus of the current studies. Inhibition is considered an executive function, and classic tasks, such as the Stroop task, have been used to measure it. Other tasks that have been used to measure inhibition include the go / no go task, stop-signal task, and anti-saccade tasks. As a counterpart to the fractionation of executive function into simpler components (and also with the componential nature of working memory), inhibition has been broken down into separate aspects.

Classifications of inhibitory control

In the adult literature, different classifications of inhibitory control have been used. Nigg (2000) classified inhibitory processes into four types of effortful inhibition: i.) interference control, the suppression of interference due to resource or stimulus competition; ii.) cognitive inhibition, the suppression of irrelevant information from working memory; iii.) behavioural inhibition, the suppression of prepotent responses; iv.) oculomotor inhibition, the suppression of reflexive saccades (oculomotor inhibition is often associated with behavioural inhibition, but is treated as separate by Nigg). Other classifications have come from Harnishfeger (1995) and Dempster (1993). Broadly speaking, their classifications follow Nigg’s in the following ways: interference control (Nigg) is equivalent to resistance to interference (Harnishfeger) and control of perceptual interference (Dempster). Cognitive inhibition (Nigg) is equivalent to the cognitive inhibition of Harnishfeger, and the control of verbal-linguistic interference of Dempster. Behavioural inhibition (Nigg) is equivalent to the behavioural inhibition of Harnishfeger, and the control of motor interference of Dempster. The similarities are not absolute, but there is agreement on the existence of and the need to distinguish between distinct components of inhibition. The nature of these distinct components of inhibition is also generally accepted.

A latent variable analysis of inhibitory control

Friedman & Miyake (2004) investigated the relationship between three inhibition-related functions, defined according to the classification of Nigg (2000). The only difference was that behavioural inhibition and oculomotor inhibition were collapsed into one function, termed prepotent response inhibition. The other two functions were resistance to distracter interference (similar to interference control in Nigg's model) and resistance to proactive interference (similar to cognitive inhibition in Nigg's model). Based on the need to use latent variable modelling, a set of tasks was chosen to measure the three latent variables corresponding to the three proposed inhibition functions (Figure 2.1). Established tasks were chosen that seemed to fit primarily into one of the three proposed inhibitory functions. Three tasks were chosen for each inhibitory function, as this is the recommended number of measured indicators (Kline, 2005). Other tasks or constructs thought to involve inhibition-related functions that were included in the analyses were random number generation, negative priming, task-switching abilities, a reading span test, and a series of questionnaires that also measured inhibitory control. Two hundred and twenty participants completed all tasks.

The latent variable analysis suggested that the most parsimonious model consisted of two inhibitory functions, with the proposed prepotent response inhibition and resistance to distracter interference functions being collapsed into one function. This leaves two separable inhibitory functions. The collapsed function, termed response-distracter inhibition, was suggested to measure a common ability of maintaining the task goal in the face of dominant (and inappropriate) responses present in the environment. The other factor resistance to proactive interference was not statistically related to the combined response-distracter inhibition factor. This may be because of the different natures of interference of the sets of tasks used to measure the inhibitory functions: proactive interference corresponded to Nigg's (2000) cognitive inhibition that was proposed to measure the ability to suppress irrelevant information from working memory, whilst both prepotent response inhibition and resistance to distracter interference (and hence response-distracter inhibition) measure resistance to interference from the environment. Latent variable analysis (and the general approach of structural equation modelling) allows for the testing of different models with different configurations of the measured tasks on different latent variables. This results in the best model being chosen in terms of theoretical basis, statistical tests and parsimony. An important point for the current study is that the authors began with hypotheses about task structures, but were then led by the latent variable analyses and theoretical constraints.

The relationship of these two inhibitory functions to the inhibitory tasks again supported the idea of there being separable components of inhibition that are able to differentially predict performance on different tasks that are thought to involve inhibition. The RNG task was related to response-distracter inhibition (but not proactive interference), the task-switching abilities tasks were related to response-distracter inhibition (again not by proactive interference), and reading span was predicted by proactive interference (not by response-director inhibition). There was no relationship between the inhibition factors and negative priming, though this was put down to the low reliabilities of the negative priming tasks

Although this study was only an initial foray into an individual difference approach to inhibitory functions, it does suggest that tasks that are designed to measure inhibition should be at the very least reliable. The low reliability of the negative priming task measures indicates that the effect was not consistent within the task, which then limited any correlation with other measures. One issue in comparing individual differences studies and experimental research in general is reliability. In experimental studies, reliability is often not calculated. In individual differences studies reliability represents the amount of systematic variance in a measure that can be associated with other variables. The lower the reliability, the lower the amount of variance that can be associated with the other variables and the lower the potential correlation between the variables (Salthouse, Siedlicki, & Krueger, 2006). Therefore low correlations between tasks in individual differences studies may be due to the low reliability of the measures, rather than the lack of an actual relationship.

Informational Processing of

	Initial Perceptual Stage of Processing	Intermediate Level	Output Stage of Processing
	Relevant information selected, irrelevant information must be ignored.	Once information has entered working memory	Relevant responses selected, and incorrect ones resisted.
Inhibitory processes classified into possible stages in informational processing.	**Interference control** (Nigg, 2000), **resistance to interference**, (Harnishfeger, 1995) and **control of perceptual interference** (Dempster, 1993).	**Cognitive inhibition** (Nigg, 2000, & Harnishfeger, 1995), and **control of verbal-linguistic interference** (Dempster, 1993).	**Behavioural inhibition** (Nigg, 2000, & Harnishfeger, 1995), and **control of motor interference** (Dempster, 1993).
Classifications according to Miyake & Friedman (2004),	**Resistance to Distracter Interference** (c.f. interference control, Nigg, 2000)**:** **Eriksen Flanker Task** (Identify a target letter that is presented either alone, or with response-incompatible letters flanking it). **Word Naming** (Name a green target word that is presented either alone or with a red distracter word). **Shape Matching** (Indicate whether a white shape matches a green shape that is presented alone or with a red distracter shape).	**Resistance to Proactive Interference** (c.f. cognitive inhibition, Nigg, 2000)**:** **Brown-Peterson variant** (learn and then free recall successive lists of words from same category) **AB-AC-AD** (learnt list of cue-target word pairs to a criterion, must learn new list of targets paired with same criterion) **Cued recall** (View one or two lists of four words, must retrieve word on most recent list that belongs to cued category, ignoring any previous lists).	**Prepotent Response Inhibition** (c.f. behavioural inhibition *and* oculomotor inhibition, Nigg, 2000) **Antisaccade task (**Cue flashes on one side of screen, must suppress reflexive saccade toward it, and look in opposite direction to identify target). **Stop-signal task** (built up pre-potent response, must withhold response when auditory signal). **Stroop task** (name colour in which colour words and neutral words are printed, ignoring dominant tendency to read the words).

Figure 2.1: Classification of tasks in Friedman & Miyake (2004)
Formed the latent variable response-distracter inhibition

Selection of inhibitory control tasks

The relationship between executive function and ToM task performance has been investigated in developmental studies, and so the area of investigation for this thesis is the role of executive function for ToM performance in adults. Evidence that this relationship exists in adults, together with evidence from clinical studies that suggest that language may not be integral to adult ToM performance, would indicate a role for executive function in ToM development and beyond, in fully developed ToM use.

Developmental evidence for the role of executive function in ToM task performance found that early performance in 'conflict' inhibition tasks predicted later ToM performance (Carlson et al., 2002). This type of task was acknowledged to also require working memory. Therefore a similar task for adult participants would also need to have some level of working memory involvement. The specific point of inhibition in conflict inhibition could be at a behavioural level, where the child processes their behaviour to the point of execution and then inhibits their response (c.f. motor inhibition or behavioural inhibition), or at a cognitive level, where the behaviour is inhibited at some point well before the point of execution (once the relevant and irrelevant information has entered working memory). For current purposes, these two potential components of inhibition were termed response inhibition and cognitive inhibition, and this potential classification of inhibitory control into two separable components has some parallel in the two latent variable inhibition model found by Friedman & Miyake (2004) in their individual differences study, and also in the classification of inhibitory control components by Nigg (2000), Harnishfeger (1995) and Dempster (1993). Response inhibition is an established executive function, and is analogous to the behavioural inhibition of Nigg (2000) and Harnishfeger (1995) and the control of motor interference of Dempster (1993). Cognitive inhibition was proposed to be analogous to the factors of cognitive inhibition (Harnishfeger, 1995; Nigg, 2000), and control of verbal-linguistic interference (Dempster, 1993). The use of structural equation modelling allows for the initial model to be changed and improved by adding or removing tasks from the different latent variables, and also by redefining the latent variables in the model (they can also be removed and new ones added).

As noted, in latent variable analysis the aim is to choose tasks that share a common variance of the theoretical construct of interest, but that differ in their incidental task demands (ideally the common variance will only be due to the common underlying theoretical construct and not from having other task characteristics in common. Attempting to choose tasks that have different incidental demands, but require the same theoretical construct addresses this issue). This analysis addresses the problem of individual task impurity as only the common variance is used to estimate the latent variable. The unshared variance is represented by separate error variances for each task chosen. This error variance also accounts for the differing, and hence unshared, task demands. The number of tasks that are used to estimate a latent variable is suggested to be at least three (Kline, 2005), though the more that can be used the more powerful the model. This technique also allows the modification of the model to improve both the statistical fit and the theoretical basis of the data found.

Therefore there were three tasks chosen to estimate the proposed latent variable of response inhibition, and three tasks chosen to measure the proposed latent variable of cognitive inhibition.

Response Inhibition

Typical response inhibition tasks include the stop-signal task (Schachar, Chen, Logan, Ornstein, Crosbie, Ickowicz & Pakulak, 2004), anti-saccade task (Klein & Foerster, 2001), and go / no go task (Wager, Sylvester, Lacey, Nee, Franklin & Jonides, 2005).

Go / No Go task

In the go / no go task, participants are shown serially presented visual stimuli. The stimuli are in two categories, go (respond) and no go (not respond). The majority of the stimuli are go stimuli, whilst (usually) one is a no go stimulus. The dominant response is therefore to respond, making the participant have to inhibit that dominant response when the no go stimulus is presented. In the current study, the stimuli were letters, and participants were instructed that they were to respond to all letters except the letter ‘K’ by tapping the spacebar.

The mechanism underlying the go no / go task is usually said to be response inhibition (Johnstone, Pleffer, Barry, Clarke & Smith, 2005), but more recent evidence has suggested that there may be elements of a 'non-motoric' stage of inhibition (or cognitive inhibition) as well as response inhibition involved. This 'non-motoric' or cognitive inhibition may alternatively be a stage at which the need for inhibition is identified (Smith, Johnstone & Barry, 2008). The decision to respond or not may also be based on the a priori knowledge of the categorical stimuli. It therefore requires decision-making, response selection and response inhibition, all high-level cognitive functions assumed to be part of executive function abilities. Therefore, compared to the stop-signal and anti-saccade tasks, the go / no go task has a lower load on response inhibition but a higher load on response selection (Rubia, Russell, Overmeyer, Brammer, Bullmore, Sharma, Simmons, Williams, Giampietro, Andrew & Taylor, 2000).

Go / No Go task (picture)

A variation on the go / no go task was developed in order to have a task that required similar resources to the go / no go task but had different incidental demands, as per the criteria for the choice of tasks in latent variable analysis. As this task relied on similar mechanisms to the go / no go task, it is thought that the task would tap response inhibition (Schmitt, Münte & Kutas, 2000), potentially together with cognitive inhibition.

Participants were presented with pictures of bird and mammals, and were trained as to what their names were. In the task, they were required to differentially respond to bird and animal pictures, but were instructed not to respond to those pictures of animals and birds whose names began with a vowel. These trials were the no go trials, compared to the pictures that began with a consonant being the go trials. This task in particular required response inhibition (to stop any activated response to a no go trial), response selection (to decide both which response to use in a go trial with the bird / mammal distinction, and whether to respond to a go or no go trial), and working memory (to recall the names of the animals in the pictures shown, which would then lead to the response selection). It is likely that the categorisation of the image into mammal or bird is available first, followed by the processing of the initial letter. This would suggest that the go / no go response is based on the initial letter (van Turrenout, Hagoort & Brown, 1997).

The picture-based go / no go task has the same underlying paradigm as the go / no go task. The various stimuli also have varying responses (name of animal begins with vowel – do not respond; name begins with consonant: type of animal: mammal – respond by pressing P; bird – respond by pressing Q). The initial decision, perhaps requiring response selection, is whether the animal is a bird or mammal. However, response inhibition should be required in order to avoid responding to an animal whose name begins with a vowel.

Stop-Signal task

Participants are shown serially presented visual stimuli, in this case either the letter 'O' or the letter 'X'. Their instruction is to respond by pressing the corresponding letter on the keyboard, unless they hear a tone, which is presented after the letter is shown. The trials can therefore either be go or stop trials. In a go trial the letter is presented on the screen until the participant responds. In a stop trial a tone is presented a short time after the letter is shown. The majority of trials are go trials, so the dominant response is to respond. The participant has to inhibit that response on the presentation of the tone.

The interval between the presentation of the letter and the presentation of the tone in the stop trials is varied by the accuracy of the participant. If the participant correctly inhibits their response in a stop trial, the interval between letter and tone presentation is increased in the next stop trial. If the participant incorrectly responds, that interval is decreased. Therefore the interval will initially vary, but will eventually oscillate around the interval at which the participant successfully inhibits 50% of the time on the stop trials.

The stop trials in a stop-signal task require participants to inhibit an already activated motor response (Aron, Fletcher, Bullmore, Sahakian & Robbins, 2003), as the stop-signal is given shortly after the stimuli (or go signal) is presented (the go signal needs to be converted into a no go signal), which is the definition of response inhibition. Any errors made would be due to not being able to stop the dominant response. Therefore the theoretical construct underlying this task may be response inhibition.

Cognitive Inhibition

This was based on the idea of cognitive inhibition being used at the stage at which the information to be processed has entered working memory (whether relevantly or irrelevantly), The choice of tasks to measure this potential latent variable were a cued recall task (Tolan & Tehan, 1999), a Simon task (Peterson, Kane, Alexander, Lacadie, Skudlarski, Leung, May & Gore, 2002), and a shape-matching task (DeSchepper & Treisman, 1996). The choice of tasks was also informed by those used by Friedman & Miyake (2004).

Cued Recall task

For the cued recall task participants were required to recall a target word from the second of two lists of four words when prompted by a cue word. In interference trials, there was a foil word in the first list which was also a (better) match to the cue word – therefore to respond to the cue word correctly with the target word, participants need to inhibit the irrelevant foil word (or deal with the interference caused by the irrelevant information of the foil word).

More specifically, the cued recall task presented participants with two lists of words, from which they were then cued to recall a word at the end of each trial (after a distraction task). The first list of words was read aloud, and the second set silently, followed by a distraction task. The participants were instructed to recall the relevant cued word from the most recent (therefore silently read) block. In the experimental trials the cue referred to the target word in the silent block, but also to an intrusion word in the (first) aloud block. The intrusion word was always a more common example of the cue category than the target word.

The presentation modality of the two word list may have an affect on recall ability. The 'aloud' and then 'silent' modality of the two lists should result in the maximum interference (Tolan & Tehan, 1999). There was also a distraction task between the final list and the cue (and recall position), which may have had an effect on the two word lists. The original paper suggests that short-term recall (as measured by this task) relies on phonological codes. The data suggests that input through auditory representations (rather than through visual pathways, as in the silent condition for the second word list) results in stronger phonological representations. This suggests that the phonological representation of the foil survives distracter activity when the foil is read aloud (as compared to their conditions where the foil was sometimes read silently), resulting in greater interference. The (verbal) distracter task resulted in increased degradation of the phonological traces of both the target and foil words, increasing interference for both. Much literature would suggest that the inhibitory construct tapped by this task is therefore resistance to proactive interference (from the foil word; Friedman & Miyake, 2004), also termed cognitive inhibition (Nigg, 2000).

However, a more recent study investigated the use of controlled and automatic processes in a cued recall task. The proactive interference between the foil and target words was said to be at an automatic level, and that this could be resolved using an automatic process (an age invariant process) but also with a controlled process that was used by younger participants (as in this sample). The nature of the controlled process is not clear, but may involve the selection of the target item, potentially through the suppression of the foil item (Ikier, Yang & Hasher, 2008). This may rely on response selection.

Simon task

In the Simon task participants were instructed to respond to the orientation (either left or right) of an arrow stimulus, not to the spatial position (the arrow was presented on either the left or the right of a central fixation point). The participants needed to maintain the task requirement of responding to the arrow orientation, and ignore / inhibit any interference from the irrelevant information from the arrow position. Response inhibition may be required to stop any response to arrow position before arrow direction can be processed. However, there should be a level of cognitive inhibition required in order to maintain focus on processing arrow direction and to (cognitively) ignore processing the arrow position (ignoring/inhibiting irrelevant information).

Studies have indicated that the functions associated with the resolving of the interference between irrelevant and task-relevant features are varied in nature. Sensory processing and response processing regions are both involved in a network of regions across the brain (Peterson et al., 2002), so therefore there may be a role for both dealing with cognitive interference and for response inhibition. Other studies have found that the mechanisms underlying cognitive interference in the Simon task and response inhibition in the stop-signal task may be similar (Verbruggen, Liefooghe, Notebaert & Vandierendonck, 2005). It has been suggested that in the Simon task, the irrelevant features automatically activate responses through a direct route, whilst the task-relevant features activate the correct response through a controlled route. To respond correctly participants must actively suppress the incorrect response (Ridderinkhoff cited in Wittfoth, Buck, Fahle & Herrman, 2006), implying that response inhibition may be required. Response selection may also play a role in this task. It has been cited primarily as a function required by the go / no go task (Rubia et al., 2000), but is based on the participant having a priori knowledge of the (categorical) stimuli. In the Simon task, the instructions state which domain the participant should attend to, and also which one they should ignore. This could be said to be analogous to the go / no go task conditions of go and no go.

Shape Matching task

The shape-matching task required participants to judge if a white and a green shape matched, or whether they did not. For half of these trials, a red shape was also present, superimposed on top of the green shape. The red shape therefore acted as a distracter to the main green shape. The participant needed to deal with any interference from the red distracter shape in order to correctly respond with the matching decision between the green and white shape. The shape-matching task aimed to measure resistance to distracters and resistance to inappropriate responses. This was achieved by presenting participants with a matching decision to make on a pair of shapes (the decision was whether a green shape matched the white target shape). Half the trials also presented a third (red) shape superimposed on one of the pair, acting as a distracter. The distracter shape matched the target shape when the green shape did not. In these trials participants needed to process the green shape whilst ignoring the red distracter shape. They may have also needed to deal with any ongoing interference from the distracter shape, which would require cognitive inhibition. This was anticipated to be harder to deal with when the distracter shape matched the target than when it did not.

Inhibition has been linked to processing distracter shapes (in ignoring them), but in anti-saccade tasks where they were presented prior to the critical trial (Crawford, Hill & Higham, 2005), but there is some support for the role of inhibition in the suppression of inappropriate processes by a distracter, and also in actively keeping distracters from interfering with target shapes (Endo, Saiki & Sato, 2001). Therefore there may be an element of active suppression of interference, which could be analogous to cognitive interference, but also an element of suppression of incorrect responses due to the distracter, which is more characteristic of response inhibition. Response selection may also be involved in order to determine the particular shape to attend to or process.

Summary

The response inhibition tasks all fall into the behavioural / control of motor interference categories of Nigg, Harnishfeger and Dempster respectively. The cognitive inhibition tasks do not fall as neatly into one category. The Simon and shape-matching tasks could be classified as requiring interference control / resistance to interference / control of perceptual interference, which, in Friedman & Miyake's study, was collapsed with the response inhibition factor to form a response-distracter inhibition factor. The cued recall task fits into the cognitive inhibition category of Nigg and Harnishfeger, and the control of verbal-linguistic interference of Dempster. There is therefore some ambiguity about the exact classification of the cognitive inhibition tasks from this battery. The deciding element on this classification was the point at which the inhibitory process was thought to occur. In the Simon and shape-matching tasks it was thought that the participants would deal with any interference (from position and distracter respectively) before they responded, thereby making the point at which they dealt with this interference not at the point of motor response or behavioural response, so not response inhibition either. Therefore they were classed together with the cued recall task as cognitive inhibition tasks. The cued recall task, the most typical cognitive inhibition task, may tap a process by which the utterance of the foil word needs to be inhibited at the point of recall. If this is the case, then the process would be similar to that of response inhibition, and so would load onto the same latent variable as the other tasks, as is the case.

This means that even though all of these tasks are proposed to require either response inhibition or cognitive inhibition as their primary resource, they all almost certainly require other resources in addition to either response or cognitive inhibition, and may require both response and cognitive inhibition in differing amounts. They are therefore multi-component tasks, as are most executive function tasks, and this may mean that their current classification may not be the optimum one. The executive function(s) that they require will also depend on the measures that are used in the modelling stage. The patterns of covariance may suggest alternate classifications using different theoretical constructs to response inhibition and cognitive inhibition, such as response selection (as required by the go / no go tasks), and latent variable analysis allows this flexibility in modifying a model to best fit the existing data (whilst maintaining a sound theoretical basis).

Overview

Executive function has been related to theory of mind in both developmental literature and in clinical studies. The developmental literature suggests that inhibition and working memory are linked to later theory of mind performance, especially in false belief tasks. This literature also found that tasks that tapped a construct termed as conflict inhibition, perhaps due to their additional requirements for working memory, were the best predictors of later false belief performance. However, the inhibitory constructs that relate to ToM in the developmental literature are likely to be too easy for adult participants. Therefore the adult literature on inhibition and executive function was examined. Individual differences approaches using SEM have started to be used in these studies as a way of using statistically pure measures of the theoretical constructs of interest (and hence avoiding measurement error). Therefore this approach was used in the current study to enable pure measures of executive function and theory of mind to be used to estimate potential relationships between the two. The classifications of inhibitory control in the adult literature are varied, but there is consensus on the notion of response inhibition. Cognitive inhibition has also been defined as the inhibition of task-irrelevant stimuli from working memory (Harnishfeger, 1995). Conceptually this seems similar to the processes involved in conflict inhibition tasks in the developmental literature, as there are elements of working memory and inhibitory control involved. Therefore the two components, the established construct of response inhibition and the construct of cognitive inhibition that appears conceptually similar to the construct of conflict inhibition that was related to false belief performance in children were chosen for the individual differences model.

Tasks were chosen that tapped these two constructs. Comparisons were made with the more established classifications to inform the choice of these tasks, and decisions were made based on the conceptual nature of the tasks, as well as any existing literature on the tasks themselves. In all cases the executive tasks were designed for the current study, but were based on tasks used in existing literature.

The relationship between the executive tasks was investigated using SEM (with a maximum likelihood method). This allowed the identification of a reliable and valid inhibitory factor structure. The ToM measured indicators were then examined and used to create specific latent variables. The relationships between the inhibitory factors and these ToM latent variables were then investigated using SEM. The validity of these relationships was then tested by looking at any differences in performance in high and low ability inhibitory control groups (from the same individual differences sample). This would also show if good inhibitory control resulted in ‘perfect’ ToM. As the individual differences model can not show whether any relationships found are indicative of inhibitory control actually being necessary for ToM (it only shows that there is a potentially non-causal relationship), a dual-task study was then used. This would show whether inhibitory control is necessary for ToM by utilising an inhibitory control secondary task with the same two (primary) ToM tasks from the individual differences model. The pattern of results could also show whether inhibitory control was involved in the specific aspect of taking a perspective, a finding that could show evidence of a cognitively efficient aspect of ToM (compared to ToM that has been found to be related to executive function in developmental, adult and clinical samples).

3. Method for individual differences study

The individual differences study consisted of eight separate tasks that participants completed over two separate sessions, with four tasks in each. The three tasks defined as requiring cognitive inhibition are detailed first, followed by the three requiring response inhibition. This is according to the initial definition of the tasks. The methodologies of the two ToM target tasks follow together with the task order and the rationale for that order.

Participants

One hundred and fifty-four university student participants took part in the study for course credits or the equivalent cash payment. Participant age ranged from 17 to 44, with a mean of 21.8 years and a standard deviation of 4.4 years. Written consent was gained from all participants. Thirty-one were male, and 123 were female, and 147 were right-handed and seven left-handed (two of whom used their right hand normally).

Apparatus

All the experiments were designed and presented on a 15-inch Samsung SyncMaster 793s monitor connected to a 3.00 GHz Pentium based desktop PC using EPrime 1.1 (Schneider, Eschmann & Zuccolotto, 2002) or DMDX (Forster & Forster, 2003). A standard 102 keyboard was also used for responses. A response sheet and pen were used to record the data from the cued recall task.

Cognitive Inhibition tasks

Cued Recall Task Methodology

Design

The cued recall task, based on the study of Tolan & Tehan (1999), presented the participant with blocks of four serially presented words shown at a rate of one word per second. A distracter task was then presented: this was a magnitude judgement task consisting of eight serially presented two digit numbers (presented at a rate of one per second) about which the participant had to judge aloud whether they were above or below 50. After the distracter task, a cue word was presented, and participants were asked to recall one of the words from a block. This could be from the only block of the trial (filler trials) or from the second block of two (where the first block acted as a distracter in experimental trials, but did not in control trials).

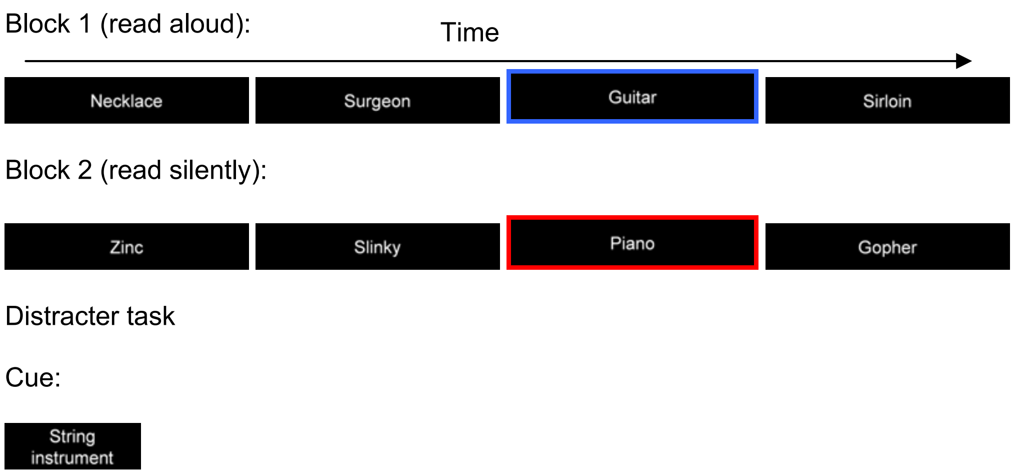

Figure 3.1: Cued Recall experimental trial (for the purposes of illustration, the blue border indicates foil word, and the red border indicates target word; these borders were not present in experimental stimuli)

The critical words in a trial were exemplars of a category, and the cue word provided a label for that category. In the experimental trials there was both a target word and a foil word from the same word category. The cue to recall therefore related to both the target and the foil words. The target word was in the second block, while the foil word was in the first block. The foil was always the more common instance of that word category (see Figure 3.1: foil = blue border, target = red border). All the words used are shown in Appendix A. Therefore the correct response is to recall the target word, and to inhibit the more common foil word (Tolan & Tehan, 1999). In the control trials, there was no foil present in the first block to interfere with the recall of the target.

The experiment consisted of 10 one block filler trials and 40 two block trials. In creating the trials for each subject, the target and foil were first randomly assigned to the different running versions (filler, control and interference trials). In both the two block trial types (20 interference and 20 control) the target and foil were placed within the randomly selected filler words to create two four-word blocks. For the 20 control trials the interfering foil was replaced by a filler item, so that the target was the only instance of the category in the list. On the interference trials, foil and target always appeared in the same serial position (on half the trials in position 2 and on the other half in position 3) in their respective blocks. For the control trials the target word was placed in the second block, position 2 in half the trials and second block, position 3 in half the trials. The ALOUD block always came before the SILENT block in order to increase interference in recalling the target word. This was followed by the distracter task and then the cue word. Trials were presented in a pseudo-random order with the constraint that there were no more than three of the same type of trial in a row, and that the blocks could not start with an interference trial.

Procedure

This task was presented using EPrime 1.1 (Schneider et al., 2002). Participants were instructed to remember only the most recent block, but were not told if the trials were two block or one block trials. They followed an on-screen instruction on how to read it (ALOUD or SILENT). Before the first block's reading instruction (ALOUD) appeared on screen, a READY prompt was shown on-screen for two seconds. The one-block trials were read ALOUD, the first block of the two block trials was read ALOUD, and the second block of the two block trials was read as SILENT. The distraction task was given before the cue was shown. After the distraction task, the cue was presented on-screen for five seconds, during which time they had to recall the correct item.

The dependent measure was the number of correct control trials minus the number of correct interference trials. This was chosen because the number of correct control trials was taken to be the measure of the participants' general recall ability (dealing with the interference caused by the mixed (ALOUD and SILENT) presentation modality, and the additional interference caused by the verbal modality of the distracter task). The interference trials additionally had pro-active interference from the foil word in the first block. The measure of participants' ability to deal with this pro-active interference alone was therefore the difference between their performance on control and interference trials. The number of omissions in either trial type was not taken into account by this measure, and this simplified interpretation of the measure because omissions have more than one interpretation. In an interference trial an omission could be due to the participant not knowing the target or foil word, or due to them not knowing the target word but knowing the foil word and being unwilling to say it. The control trial omissions are more likely to be due to forgetting the target word, though there is still the potential for not responding due to recall of a knowingly incorrect filler word. Due to these potential ambiguities in the reasons for omissions, it was decided to omit them from the measure.

Simon Task Methodology

Design

The original findings on the Simon effect were published by Simon and Wolf (1963). The current task was based on the experiment presented by Peterson et al. (2002). In this task, the participant was shown horizontally-orientated arrows (left or right), presented on the left or right of central fixation point on a screen. Participants were instructed to respond left or right, according to the orientation of the arrows, not their position. The arrow position is visually more salient than the arrow orientation. Therefore responding to the orientation requires the inhibition of any response to the position. The majority of trials were congruent (left-pointing arrow appeared on the left of the screen, right-pointing arrow appeared on the right of the screen), whilst a minority were incongruent.

The task consisted of four blocks of 102 trials each, totalling 408 trials overall. There were equal amounts of left and right arrows. In terms of trial types, there were a total of 328 congruent trials and

80 incongruent trials. In each block there were 20 incongruent trials (equal left and right) and 82 incongruent trials (equal left and right). The order of the incongruent and congruent trials was fixed in a pseudo-random sequence. The incongruent trials were balanced in terms of the direction of the arrow in the trial immediately preceding (half the incongruent trials were preceded by an arrow of the same orientation, but in a congruent position, and half were preceded by an arrow of the opposite orientation, in the congruent position). There were also no more than three arrows of the same orientation in a row (regardless of congruency).

Procedure

This task was presented using EPrime 1.1 (Schneider et al., 2002). Participants were instructed to respond to the orientation of the arrow (left or right) and to ignore the position of the arrow. The trials began with a fixation point on-screen for 200ms, followed by the arrow for a maximum of 1300ms, or until a response was made, upon which time the fixation point was presented again (to start the next trial).

Other studies (Kumada & Humphreys, 2002; Peterson et al., 2002) investigating the Simon effect have compared the RTs on the congruent and incongruent trials as a basis for their results, but as this study is using an individual differences approach, a single measure was needed. The difference between incongruent and congruent trials was taken to be a measure of any inhibitory processing cost present only in the incongruent trials (any processing cost common to the incongruent and congruent trials would be accounted for).

Shape-Matching Task Methodology

Design

The experiment of DeSchepper and Treisman (1996) was used as the basis for this task. Participants were shown a green-outlined shape (acting as a target) and a white-outlined shape, presented on a black screen. The participant had to decide whether the white shape matched the target green shape (see Figures 3.2, 3.3, 3.4 & 3.5).

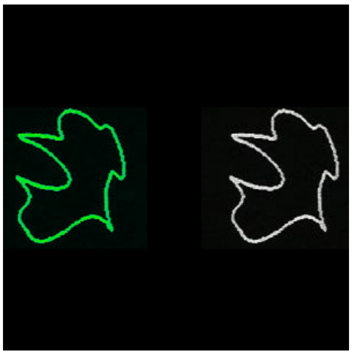

Figure 3.2: No distracter, Match trial

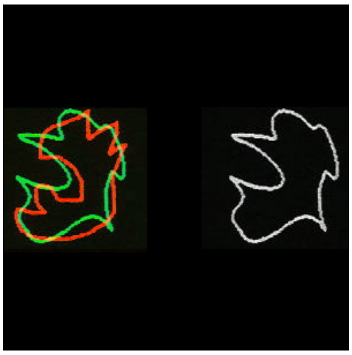

Figure 3.3: Distracter, Match trial

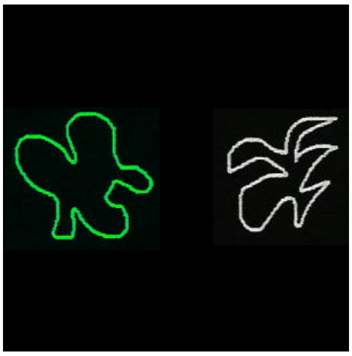

Figure 3.4: No distracter, No Match trial

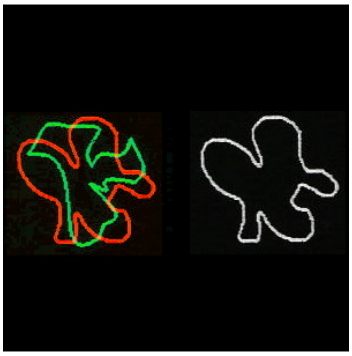

Figure 3.5: Distracter, No Match trial

In the experimental trials, a red-outlined shape is also presented directly on top of the green target, thereby partially occluding it. The red shape acted as a distracter (from the target shape). Any processes involving the distracter shape needed to be inhibited in order to correctly match the green and target shapes.

The shapes used were taken from DeSchepper and Treisman (1996), and consisted of eight random shapes. There were eight green shapes, eight red shapes and eight white shapes (see Appendix A). The number of times each type of shape occurred was balanced across the task. There were a total of 112 trials, 56 distracter trials and 56 no-distracter trials. Of the distracter trials, 28 were matching trials (green shape = white shape, correct response = yes; Figure 3.3) and 28 were non-matching trials (red shape = white shape, correct response = no; Figure 3.5). For the no-distracter trials, half were matching trials (Figure 3.2) and half were non-matching trials (Figure 3.4). The task was split into four blocks of 28 trials, of which half were distracter trials (half of which were matching, half non-matching), and half were non-distracter trials (half matching, half non-matching). The constraints were that no block began with a matching trial, and there were never more than three of any trial type in a row. There were also no more than three trials in a row in which the same type of shape was presented (in any colour).

Procedure

This task was presented using EPrime 1.1 (Schneider et al., 2002). Participants were instructed to decide whether the green (target) shape matched the white shape. They were told to ignore the red (distracter) shape when it was present. Each trial had the following procedure: the participants were presented with a READY prompt to which they had to respond to in order to proceed. A blank screen was then shown for 1100ms, followed by a fixation point for another 500ms. The shapes were then presented until the participant responded. Then another blank screen was shown for 100ms, upon which the READY prompt appeared for the start of the next trial. The measure used was the difference in reaction times between the distracter no-match (Figure 3.5) and the no distracter match (Figure 3.2) conditions. This was because in the distracter no match condition, the distracter matched the white shape, thus increasing potential interference for the condition. The distracter match condition was considered to be the simplest condition, with the least potential interference. Therefore the difference in response time between these conditions should give a measure of the maximum interference caused by the distracter shape. The use of a response time difference between conditions as a measure is similar to that used by both DeSchepper and Triesman (1996) and Friedman and Miyake (2004).

Response Inhibition tasks

Go / No Go Task

Design

The task was based on the experiment by Wager et al. (2005). Participants were shown serially presented letters on-screen that they were required to respond to by pressing the spacebar (go trials). This was the requirement for all letters except for the letter K (which was a no go trial).

The experiment consisted of eight blocks of 65 experimental trials (each block also had an additional five trials at the start that were eliminated in analyses as practice trials – this was an attempt to avoid any possible learning effects at the start of each block). There were either eight or 10 no go (K) trials in each block, and hence 57 or 55 go trials in each block. Overall there were 72 no go trials, and 448 go trials. The low percentage (13.85%) of no go trials should accentuate the dominant tendency to respond to all trials, so increasing the likelihood of errors in responses to the no go trials. No letter was preceded by itself and no block could start with a no go trial.

Procedure

This task was presented using EPrime 1.1 (Schneider et al., 2002). Participants viewed a series of letters presented on a computer screen to which they had to respond to (by pressing the spacebar). They were instructed to respond to all letters except for the letter K. If the participant responded incorrectly to the letter K, a tone would be heard. Each trial consisted of an initial fixation cross for 250ms, followed by a letter. Each letter remained on-screen for 500ms, or until the participant responded.

The standard measure used in the task was the number of times that the participants incorrectly responded when the letter K was presented on-screen (the false alarm rate, or FAR). This measured the participants' ability to inhibit the dominant (go) response when shown a no go (K) trial.

Go / No Go Picture Methodology

Design

This task was based on the study of Schmitt et al. (2000). Participants were shown images of either birds or mammals. If the image was a bird, the participant was instructed to respond by pressing the Q key; if the image was a mammal they were instructed to respond by pressing the P key. The go / no go decision to respond or not was based on the initial letter of the name of the animal: if the name began with a consonant, the participant was instructed to respond, and if it began with a vowel, they were instructed not to respond. The assumption was that when the image is shown to a participant, the semantic information (the bird or mammal category) was available before the phonological or orthographical information (the initial letter). The Q / P response would then be available before the point of deciding to respond (go) or not (no go), and so the decision to respond or not would be based on the initial letter of the name of the animal in the image (van Turrenout et al., 1997). As the majority of the animal's names began with a consonant, to which participants had been instructed to respond, the dominant response was to respond. Therefore when an image whose initial letter was a vowel was presented, to which they had been instructed to not respond, participants had to inhibit that dominant response, which required response inhibition. The possible images were as in Table 3.1.

Table 3.1

Image Types

Image	Consonant / Vowel	Correct Response	Trial Type
Mammal	Consonant	P	Go
	Vowel	None	No go
Bird	Consonant	Q	Go
	Vowel	None	No go

The task was composed of eight blocks of either 22 or 23 trials (a total of 180 trials). In a block four or five trials were no go trials, and the rest go trials. Overall (and as much as possible within blocks) the numbers of bird images and mammal images were balanced: there were a total of 45 bird images and 45 mammal images. Of the 45 bird images, 36 began with consonants, and nine began with vowels. The same was true of the 45 mammal images. Images were repeated twice within the experiment (but never in the same block). There were no more than three trials in a row of the same image type (bird or mammal). The initial three trials in each block were removed from the actual analyses as practice trials as an attempt to lessen any learning effect. The images used can be seen in Appendix A.

Procedure

This task was presented using EPrime 1.1 (Schneider et al., 2002). The participants were shown (serially) all the images of birds and mammals, together with their names, at the start of the experiment (each image remained on-screen until the participant pressed a key). They were then shown the images again, in a different order, for 3000ms, in which time they were instructed to name each image. This was done in order for errors made in the actual experiment to be attributable to inhibition errors rather than due to simply not knowing the names of the animals (pilot work[1] had already established that most people were familiar with the mammals and birds used). During the experiment the images were presented on-screen for 750ms, or until the participant responded. If the participant responded incorrectly (by responding to a mammal as a bird, or to a bird as a mammal, or by responding at all to an image whose name began with a vowel), then a tone was heard. The measure taken was the false alarm rate (as in the normal go / no go task) of response to no go trials (images beginning with a vowel).

Stop-Signal Task

Design

The task was based on the task of Schachar et al. (2004). The procedure consisted of presenting stimuli to the participant, who had to respond by pressing the appropriate key. The main instruction was to respond to all trials, apart from those in which a tone was presented at an interval (delay) after the stimuli was shown. For these trials the instruction was not to respond.

[1] 28 participants were tested on the battery of executive function tasks. As part of this, they were asked to rate the familiarity of the names of the animals they were shown in the go / no go (picture) task.

The stimuli were X and O, and the response was to press the X (for X) or O (for O) key in response. The normal response trials had no tone, and are referred to as go trials. The trials that contained a tone are referred to as the X or O stimuli stop trials, in that these are the trials in which the participant had to inhibit their initiated response to the X or O stimuli. The tone delay (the time between the appearance of the stimuli and the presentation of the tone) was varied according to the response to the previous stop trial. The initial delay was 250ms, which was increased by 50ms in the next trial if the subject correctly inhibited their response on the trial, or was decreased by 50ms in the next trial if the subject incorrectly responded to the trial. This was termed a 'dynamic tracking procedure' by Schachar et al. (2004), in that if the subject was not responding correctly, the tone delay would decrease until the subject began correctly (not) responding on stop trials, and would increase if they were correctly (not) responding until they made an error and responded on stop trials. This dynamic tracking allowed the inhibition demands to be kept relatively constant across the experiment.

The number of X and O stimuli was balanced (in both go and stop trials, and hence overall). Out of a total of 256 trials, 64 (25%) were stop trials, and 75% were go trials. The trials were divided into eight blocks, each with eight stop trials and 24 go trials.

Procedure

This task was presented using EPrime 1.1 (Schneider et al., 2002). Each trial proceeded in the following way: an initial fixation point was presented for 500ms. The stimulus was then shown on-screen for a period of 1000ms, or until the participant responded. After the stimulus screen, a blank screen was shown for 2000ms, or until the participant responded. This gave a total time of 3000ms for the participant to respond. The tone was heard in stop trials at a variable delay after the initial presentation of the stimulus.

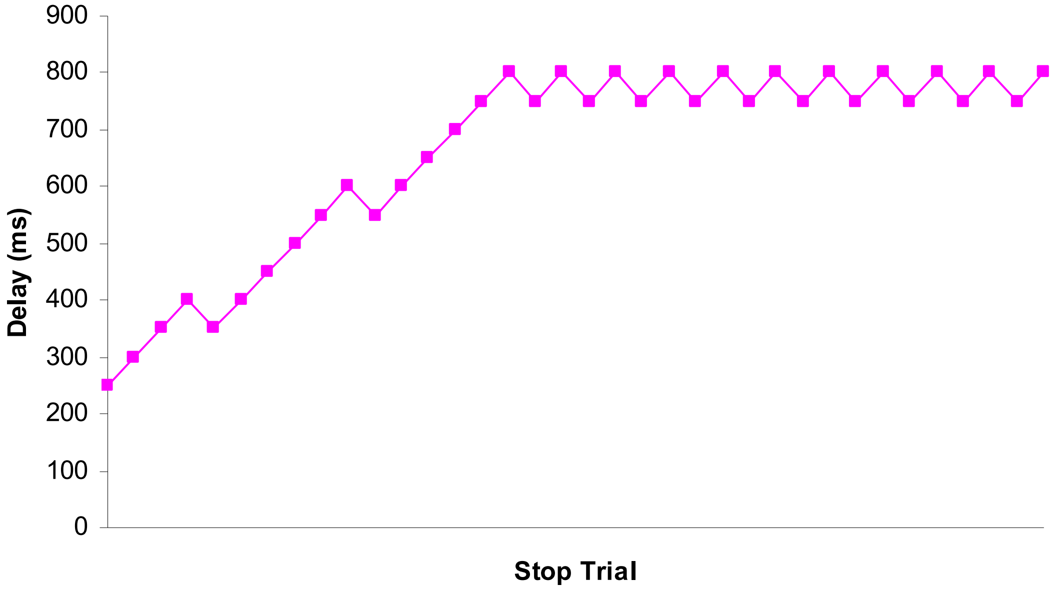

Figure 3.6: Changes in tone delay through trials

Figure 3.6 is an illustration of how tone delay would initially change in one direction, before reaching a stable alternation about the subjects' mean delay score.

The standard measure used in most stop-signal tasks is that of Stop Signal Reaction Time (SSRT) which is calculated by subtracting the median tone delay (of the stop trials) from the median reaction time to the go trials, thereby giving:

SSRT = median Go RT – median Stop RT

Theory of Mind target tasks

Keysar Task

Design

This task modifies the experiment of Keysar et al. (2003) by being created on a computer, with no subsequent need for an actual confederate (Apperly, et al., submitted). The participant was shown a grid containing several objects. An instructor (a sprite located to behind and to the right of the grid) gave the participant instructions to move individual objects around the grid. The participant was required to follow the instructions by clicking on the appropriate object using the mouse provided, and then pretending to move it as instructed (Figure 3.7).

Each grid had five slots that were covered on the instructor's side, so objects located in these covered slots were not visible from the instructor's perspective. In an experimental grid, a critical instruction was given by the instructor that could refer to a target object (mutually visible to the participant and instructor), or to a competitor object (located in one of the covered slots, and so visible only to the participant). In order to choose the correct (target) object, the participant needed to consider the instructor's perspective. The remaining objects in the grid were unrelated. In the equivalent control grids, the competitor object was replaced by another unrelated object.

There were two separate types of experimental trials. In ambiguous experimental trials, the object referred to in the critical instruction could either be the target object or the competitor object ('mouse' could refer to a mouse or a computer mouse). In these trials the instruction given by the instructor could refer to both competitor and target objects, which could prompt the participant to notice the ambiguity, and then, perhaps, to solve it by taking into account the instructor's perspective. By failing these trials participants are still failing to take into account the instructor's perspective and so failing to use ToM.

In relational experimental trials the object was defined by its size or position that differed for the participant and the instructor. This was done by having three objects of differing sizes or positions visible to the participant, only two of which were visible to the instructor. Therefore the third object visible only to the participant was always the competitor object (Figure 3.7). In the relational trials, the competitor object fitted the instructions best if the participant did not take into account the instructor's perspective. In order to follow the instruction correctly, participants needed to consider the instructors perspective. Any errors made should be attributable to the participant not taking into account the point of view and knowledge of the instructor, and hence not using and relying on their ToM (for example moving the golf ball rather than the tennis ball in Figure 3.7).

There were a total of 32 grids, each with four x four slots, five of which were occluded from the point of view of the instructor. The remaining 11 slots were visible to both the participant and the instructor. There were four different patterns of occluded slots in the grid, and every grid contained eight items. Half the grids were experimental, and these all had an equivalent control grid. The critical instruction was the same for equivalent grids. There were a total of 105 instructions across the 32 grids. The number of instructions (including critical) for each grid varied between three and five, and the position of the critical instruction also varied, between first and fourth. The number of instructions and the position of the critical instruction were identical for equivalent experimental and control grids. No more than two experimental or control grids were presented in a row (and then were of different slot patterns).

Procedure

This task was presented using EPrime 1.1 (Schneider et al., 2002). The participants were instructed to follow the instructions of the instructor in moving objects around each grid, and were told that the instructor did not know what was behind in the covered slots (instructions are in Appendix A). This was shown by an example grid viewed from both the participants' view, and also from the instructor's view. As they had been shown an example of the instructor's view, they had the explicit knowledge that the instructor had a different perspective to their own. Therefore, any mistakes in the experimental conditions should be attributable to not taking the instructor's perspective into account when interpreting his utterance and choosing which object to move. The measures used in the task were the number of errors made in relational trials and the number of errors made in ambiguous trials.

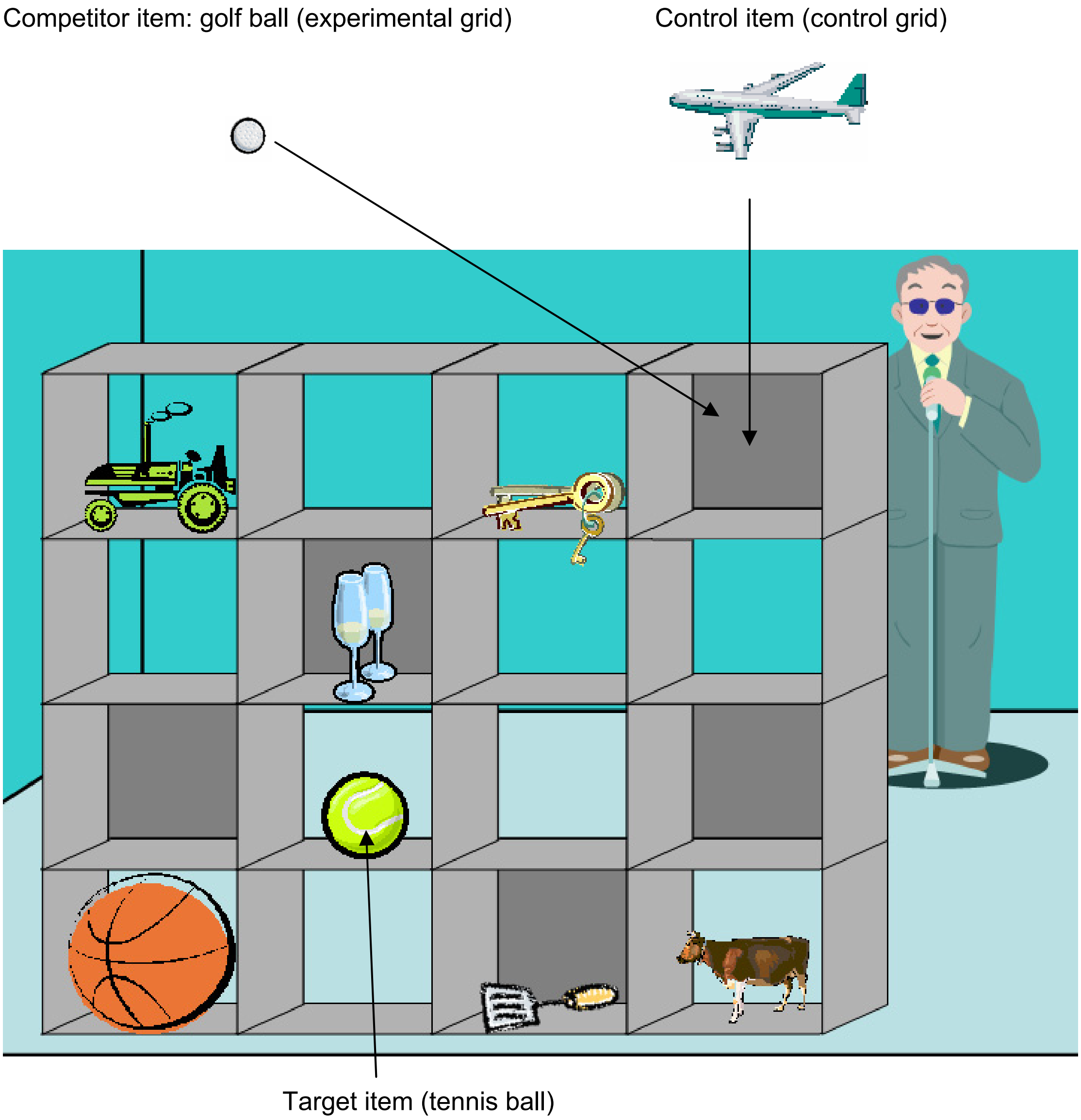

Figure 3.7: Example grid for a relational grid of the Keysar task

Critical instruction: Move the small ball down one slot

In the experimental grid, the smallest ball from the participant's viewpoint is the competitor item (golf ball), but the target item (the smallest ball from the director's viewpoint) is the tennis ball.

In the control grid, the smallest ball from the participant viewpoint is the target item (tennis ball), which is the same as for the director.

Visual Perspective task

Design

This task investigated ToM processing (Samson et al., submitted). Participants saw an image of a room, with an avatar standing in the center. Red circles were pinned on the walls (stimuli were created using the 3D animation program Poser 6, © Curious Lab). The circles were pinned on the left or the right wall (with a total of zero to three circles) and the avatar faced either the left or the right wall. In half of the trials the avatar and the participants could see the same amount of circles (consistent perspective condition, see Figure 3.8) and on the other half of the trials they saw a different amount of circles (inconsistent perspective condition, see Figure 3.9). Female participants were presented with a female avatar and male participants were presented with a male avatar.

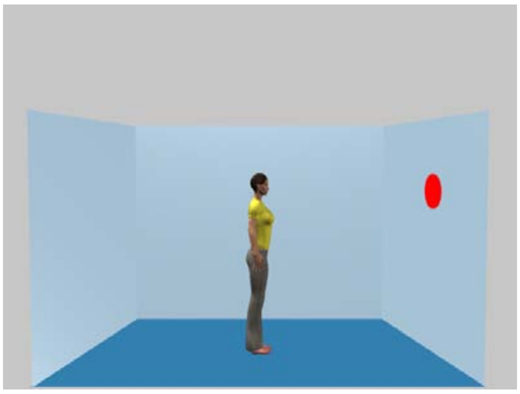

Figure 3.8: Consistent perspective

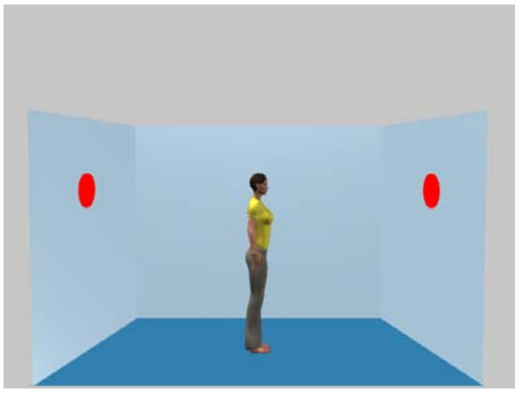

Figure 3.9: Inconsistent perspective

There was a total of 96 matching trials: 48 trials in which participants were asked to verify their own perspective (with 24 consistent perspective trials and 24 inconsistent perspective trials) and 48 trials in which participants were asked verify the avatar's perspective (with 24 consistent perspective trials and 24 inconsistent perspective trials). In addition to these 96 test trials, 96 mismatching filler trials were included (with the same distribution as for test trials) as well as 16 additional anti-strategy filler trials (eight matching and eight mismatching in which no circles were pinned on the wall). The 208 items were split into four blocks of 52 items

Procedure

This task was presented with DMDX (Forster & Forster, 2003). Participants were cued with a verbal perspective description that informed them which perspective to take (“you” versus “he”/”she”) and which perspective content to verify (i.e. a number between zero and three) before being shown the image. They were then asked to decide whether the cue information matched the relevant content shown in the image. In half of the trials, the cue matched the image and on the other half the cue did not match the image. An initial fixation cross was on-screen for 750ms, followed by the cues, also on-screen for 750ms. The gap in between fixation and cues was 500ms. The following picture remained on-screen until the participant responded. If no response was received within 2000ms of the picture being on-screen, the trial was recorded as no response.

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It was expected that the processing of either perspective (avatar or self) would be affected by interference from the other perspective – that participants would be unable to stop processing the irrelevant perspective (Samson et al., submitted). Therefore there were two measures for this task. The first was the difference in reaction time between the consistent and inconsistent conditions for the self perspective trials. This gave a measure of the degree of interference of the avatar’s perspective to the processing of the self perspective. The second measure was the difference in reaction time between the consistent and inconsistent conditions for the other perspective. This gave a measure of the degree of interference of the self perspective to the processing of the other perspective.

Task order

The order of the tasks was fixed so that participants were exposed to identical stimulus contexts, where the context includes both the actual stimuli, but also the order in which they were presented. This is standard practice in individual differences research (Carlson & Moses, 2001; Carlson et al., 2004; Friedman & Miyake, 2004; Miyake et al., 2000; Miyake, Friedman, Rettinger, Shah & Hegarty, 2001). This is because the correlations between tasks in one task order may not be the same as in a different task order, so calculating the overall correlation from these values may result in a different value than either of the sub-correlations. Not counter-balancing the task orders in an individual-differences study avoids this problem (though the task order chosen may have different correlation values compared to an alternative task order).

The task order was also constrained by there being no more than two of each type of task (cognitive inhibition, response inhibition, theory of mind) in a row. This was because of the possibility that there is a limited, finite pool of resource for executive components, especially for inhibition (Muraven & Baumeister, 2000), so if several of the same type of task were completed one after another, the final task may be affected by the lack of response inhibition capability left to the participant, thereby not giving a true measure of their actual response inhibition capacity. Therefore the overall task order was as follows:

Go / No Go Task (response inhibition)

Simon Task (cognitive inhibition)

Visual Perspective Task (ToM)

Shape-Matching Task (cognitive inhibition)

Go / No Go Task (response inhibition)*

Stop-signal Task (response inhibition)

Keysar Task (ToM)

Go / No Go (picture) Task (response inhibition)

Cued Recall Task (cognitive inhibition)

* This was a repeat of the first task in the session. This is being included to compare performance at the start to the end of the session, to see the effect of a.) fatigue on performance, and also b.) the possibility of the reduction in the resource of self-control affecting performance by the end of the session. The varying changes in performance for each participant can be compared to see if the effect over the session is a common one or not.

The tasks were split into two sessions. The first session lasted for approximately 70 minutes and consisted of the Go / No Go, Simon, Visual-Perspective and Shape-Matching tasks, as well as the repeat of the Go / No Go task. The second session lasted for approximately 90 minutes and consisted of the Stop-Signal, Keysar, Go / No Go (picture) and Cued Recall tasks. There were breaks within each task and between each task, so that participants were not tested continuously for the period of the sessions. Participants did the sessions on the same day (with a break between them) or on separate days (maximum gap between sessions was three weeks).

4. Individual Task Results

Initial data screening

The data screening process consisted of several steps. The following steps were adapted from those used by Friedman and Miyake (2004) and Oberauer (2005) in order to reduce the effect of any extreme response time values on the mean.

The critical dependent variables of the various tasks were calculated, and any values more than three standard deviations above or below the task mean were replaced by the cut-off value (of three standard deviations above or below the mean). All pairwise plots were then examined for nonlinearity and heteroscedasticity. The distributions of the critical dependent variables were then checked, as were univariate outliers, and any transformations were carried out. Checks for multivariate outliers were then done, and finally the variance of each variable was examined and modified as per Kline (2005). Each task required different calculations for its critical dependent variable, which are all detailed below. The reliability of all the critical measures was calculated by adjusting split-half correlations using the Spearman-Brown prophecy formula (Salthouse et al., 2006). Each task was first analysed individually to establish that the expected effects were observed.

Inhibitory control tasks

Simon task

The data were trimmed by condition for each participant individually, looking at correct responses only (5.3% were incorrect responses). Response time values that were more than three standard deviations away from the condition mean for a participant were replaced by the cut-off value (of three standard deviations from the condition mean). A 2 x 2 repeated-measures ANOVA was used to examine the data. The factors were position (left or right on screen) and orientation (left or right). The measure was the mean response time for each condition.

There was no effect of the position of the arrow on the response time of participants ($F_{(1, 152)} = 0.77$, $p = 0.38$, $\eta_p^2 = 0.01$), whilst there was a significant effect of orientation ($F_{(1, 152)} = 36.34$, $p \le 0.01$, $\eta_p^2 = 0.19$). The response times indicate that responses to a left orientated arrow were significantly slower than to right orientated arrow (left = 529.49ms > right = 518.76ms). This can be explained by there being 146 right-handed participants, as compared to only seven left-handed participants, as participants responded with both hands. If handedness was included as a covariate, the effect size of orientation was reduced ($F_{(1, 151)} = 4.53$, $p = 0.04$, $\eta_p^2 = 0.03$), but there was also a main effect of position ($F_{(1, 151)} = 4.23$, $p = 0.04$, $\eta_p^2 = 0.03$). This suggests that the majority of right-handed participants resulted in the faster response times to the right orientated arrows.

There was a significant interaction between position and orientation ($F_{(1, 152)} = 567.16$, $p \le 0.01$, $\eta_p^2 = 0.79$), as shown in Figure 4.1. Further analyses (2 –way ANOVAs) were conducted to examine the nature of the interaction.

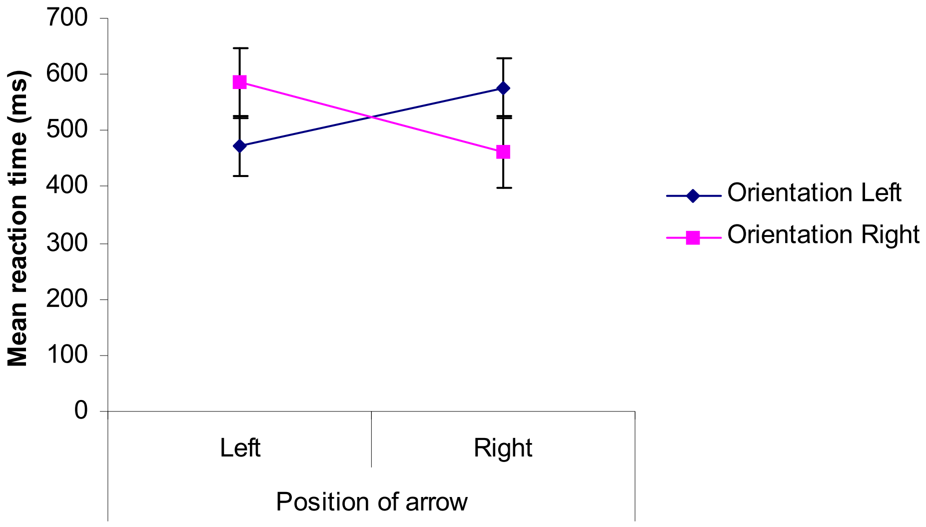

Figure 4.1: Mean response times (and standard error) to differing positions and orientations of arrow

At position = left, there was a significant difference between the response time to the left and right orientated arrows ($F_{(1, 152)} = 423.14$, $p \le 0.01$, $\eta_p^2 = 0.74$), with the responses to the left orientated arrow being significantly faster than the responses to the right orientated arrow (left = 473.61ms < right = 576.44). At position = right, there was a significant difference between the response time to the left and right orientated arrows ($F_{(1, 152)} = 574.94$, $p \leq 0.01$, $\eta_p^2 = 0.79$), with the responses to the left orientated arrow being significantly slower than the responses to the right orientated arrow (left = 585.12ms > right = 461.29ms).

When the arrow orientation was left, there was a significant difference in response time between left position and right position ($F_{(1, 152)} = 521.34$, $p \leq 0.01$, $\eta_p^2 = 0.77$), with the responses to the arrows in the left position being significantly faster than to those in the right position. In the right arrow orientation condition, there was also a significant difference between arrow positions ($F_{(1, 152)} = 445.31$, $p \leq 0.01$, $\eta_p^2 = 0.75$), this time with the response to arrows in the left position being significantly slower than the response to those in the right position. The Simon effect and these interactions are shown in Figure 4.1.The pattern of errors showed a similar effect (proportion of errors for left (position) – left (orientation) = 0.04, for right – right = 0.03, for left – right = 0.14, for right – left = 0.13) so showing no evidence of a speed – accuracy trade-off.

This pattern of results clearly demonstrates the Simon effect, focusing on the ability to select between competing stimuli. The interference effect is caused when the irrelevant features of a task are inconsistent with the task-relevant ones. In this version the irrelevant feature of the stimuli was the spatial location, and the task-relevant feature was the orientation of the arrow stimuli. In this task, there was better performance when the arrow direction is congruent with the position of the arrow (left orientated arrow in the left position; right orientated arrow in the right position). When the arrow direction and arrow position are incongruent, there is an increase in response time (to get to the correct response). This is also due to the competition between the (overlearned) dominant response of the position of the arrow guiding the response, and the actual response required by the task, which is guided by the arrow direction.

The critical dependent variable of the Simon task was the difference between the mean response times to incongruent stimuli and congruent stimuli. The reliability of this measure was satisfactory (Table 4.3). This was taken to measure the interference between the dominant response and correct response to the incongruent stimuli, interference that should require inhibitory control to resolve. Any values more than three standard deviations away from the mean were replaced by the cut-off value (of three standard deviations above or below the mean).The distribution was examined, and was found to be skewed, with one outlier (Table 4.3). The Simon task was square root transformed (plus a constant of 19.87 in order to remove negative values), resulting in a normal distribution (Table 4.4).

Shape-matching

The data were trimmed by condition for each participant individually, looking at correct responses only (5.1% of the responses were incorrect). Response time values that were more than three standard deviations away from the condition mean for a participant were replaced by the cut-off value (of three standard deviations from the condition mean). A 2 x 2 repeated-measures ANOVA was used to examine the data. The factors were distracter (present or not) and match (did the target match the green shape, yes or no) and the measure was the mean response time for each condition.

There was an effect of distracter ($F_{(1, 152)} = 132.48$, $p \leq 0.01$, $\eta_p^2 = 0.45$). If the distracter shape was present, the response time was significantly longer than when the distracter shape was not present (distracter = 1296.10ms > no distracter = 973.07ms). There was also an effect of match ($F_{(1, 152)} = 28.83$, $p \leq 0.01$, $\eta_p^2 = 0.16$). Participants took significantly longer to respond to trials in which the green shape did not match the white shape than to trials in which the green shape did match the white shape (match = 1093.12ms < no match = 1176.05ms). There was a marginal interaction between distraction and matching ($F_{(1, 152)} = 3.54$, $p = 0.06$, $\eta_p^2 = 0.02$), as can be noted in Figure 4.2. The errors are similar for all conditions (proportion of errors in distracter no match condition = 0.07, in distracter match condition = 0.05, in no distracter no match condition = 0.04, in no distracter match condition = 0.04), indicating that there was no particular trade-off between speed and accuracy.

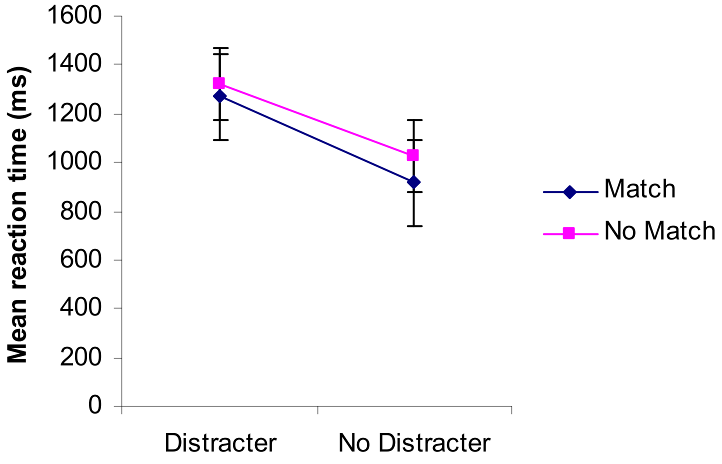

Figure 4.2: Mean response time (and standard error) to process green and target shapes by condition

The presence of the distracter shape interferes with the processing of the green shape (in matching the white target shape). The (marginally) increased response time to the non-matching trials in the distracter condition can be put down to the fact that when the green and white shapes do not match, the distracter shape does match the white target shape. Therefore the participant must stop any potential matching response caused by the distracter and target shapes matching, as well as judging that the green shape does not match the white shape. In the no distracter condition, the matching trials are also easier to respond to (in terms of response time) than the non-matching trials.

The critical dependent variable was chosen to be the difference in mean response time between the distracter no-match condition and the no distracter match condition. The distracter no-match condition appeared to have the largest amount of interference from the distracter shape, as this shape matched the target. The no distracter match condition had the least amount of interference, and gives a baseline measure of the response time to the simple matching process. The difference between these conditions is therefore a measure of the interference caused by the distracter shape only, which should require inhibitory control. The reliability of this measure was adequate (Table 4.3). Any values more than three standard deviations away from the mean were replaced by the cut-off value (of three standard deviations above or below the mean). The distribution of the critical shape matching task dependent variable was extremely non-normal, with three outliers (Table 4.3). The critical dependent variable underwent a log 10 transformation resulting in a normal distribution (Table 4.4).

Go / No Go

As the data for the go / no go task were errors, they were not trimmed (overall 8.5% of the responses were incorrect). The data were analysed using a 2 x 2 repeated-measures ANOVA, with trial type (go v no go) and position (start v end) as repeated measures. The dependent variable was the proportion of errors made.

There was a significant effect of trial type ($F_{(1, 153)} = 219.78$, $p \leq 0.01$, $\eta_p^2 = 0.59$), with significantly higher proportion of errors in the no go condition than in the go condition (no go = 0.27 > go = 0.06). There was no difference in the performance of participants in the task carried out at the start of the session and the performance in the task carried out at the end of the session ($F_{(1, 153)} = 0.01$, $p = 0.97$, $\eta_p^2 = 0.01$), and there was no interaction between trial type and position ($F_{(1, 153)} = 2.28$, $p = 0.10$, $\eta_p^2 = 0.02$) (see Figure 4.3).

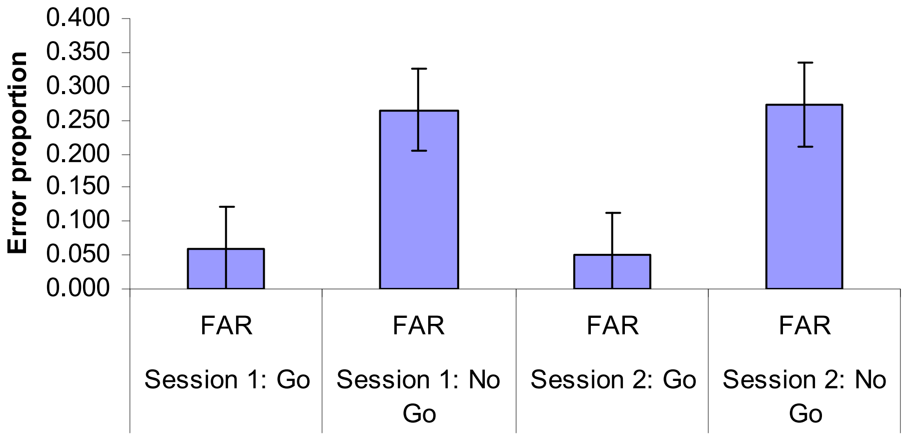

Figure 4.3: Proportion of responses (and standard error) to no go trials by condition and session

As expected, participants made more errors in the no go condition. This is because of the difficulty in inhibiting the dominant response of tapping the spacebar in no go trials, compared to carrying out that dominant response in go trials. They also had a priori knowledge of the categorical stimuli to which they had to respond and of that to which they had to not respond. The dominant response of tapping the spacebar in response to 25 of the 26 possible letter stimuli resulted in there being errors in inhibiting that dominant response when the letter K was presented.

As there was no difference between participant performance in the first and second sessions, the false alarm rate was collapsed over the two sessions. The critical dependent measure was the overall false alarm rate for the task. This was the proportion of no go trials that the participants incorrectly responded to. The higher this proportion, the less inhibitory control exhibited by the participant (inhibitory control is required to inhibit the dominant response of responding). The reliability of this measure was excellent (Table 4.3).The distribution of this dependent variable was non-normal, with two outliers (Table 4.3). The dependent variable was square-root transformed, resulting in a normal distribution (Table 4.4).

Go / No Go (picture)

As the data for the go / no go (picture) task were errors, they were not trimmed. The data was analysed using a 2 x 2 repeated-measures ANOVA, with trial type (go v no go) and image type (mammal v bird) as the factors. The measure was the proportion of errors made in each condition. Overall 25.1% of the responses were incorrect.

There was a main effect of trial type ($F_{(1, 150)} = 128.51$, $p \leq 0.01$, $\eta_p^2 = 0.46$), with a significantly higher proportion of errors in the no go condition than in the go condition (no go = 0.42 > go = 0.21). There was a significant effect of image type ($F_{(1, 150)} = 43.95$, $p \leq 0.01$, $\eta_p^2 = 0.23$), with proportionally more errors made with bird images than with mammal images (bird = 0.34 > mammal = 0.29). There was no interaction between trial type and image type ($F_{(1, 150)} = 0.70$, $p = 0.41$, $\eta_p^2 = 0.01$) (Figure 4.4).

To check that both image conditions showed the expected no go effect they were analysed separately. For the bird images, there was a significant difference between the error proportion in go and no go trials ($F_{(1, 150)} = 90.85$, $p \leq 0.01$, $\eta_p^2 = 0.38$; no go = 0.44 > go = 0.24), and this was also true for the mammal images ($F_{(1, 150)} = 106.92$, $p \leq 0.01$, $\eta_p^2 = 0.42$; no go = 0.39 > go = 0.18), so both conditions showed the no go effect.

As the aim was to have an overall critical measure (collapsed across bird and mammal images), the trial types were also analysed. In the go trials, there was a significant difference between the image types ($F_{(1, 150)} = 65.64$, $p \leq 0.01$, $\eta_p^2 = 0.30$), with more errors for the bird images compared to the mammal images. In the no go trials, there was also a significant difference between image types ($F_{(1, 150)} = 8.28$, $p \leq 0.01$, $\eta_p^2 = 0.05$), again with a higher proportion of errors for the bird images compared to the mammal images.

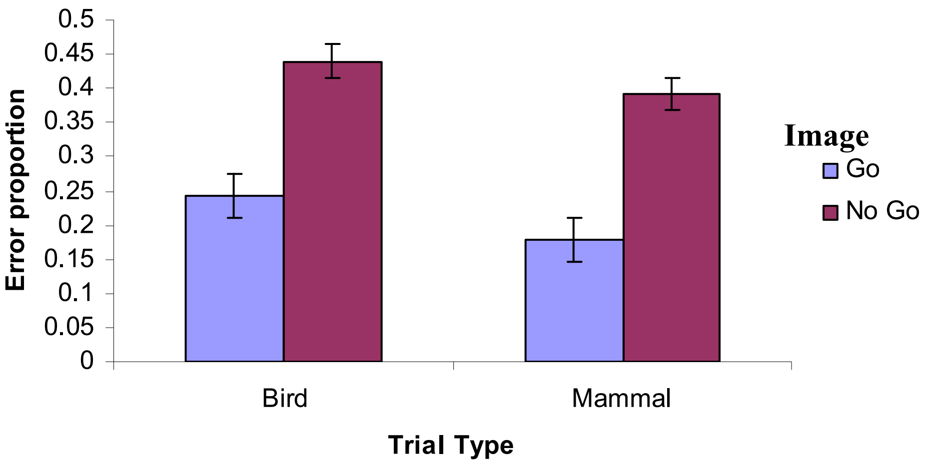

Figure 4.4: Go / No Go picture task error proportions (and standard error) by trial and image type

The results of this task showed a similar pattern overall to the go / no go task. Both image types showed the same no go effect, but the error proportion of the bird images was significantly higher in both the go and no go conditions.

Participants were shown the images to be presented in the task, together with the names, before the start of the session. Their immediate recall of these names was also tested (with images without their names). Participants accurately identified the majority of the no go images for both birds and mammals. The higher proportion of errors for the bird images may be due to the homogeneity of the bird images compared to the mammal images. However, the mammal and bird image no go error proportions were significantly correlated (see Table 4.1).

The aim was always to have an overall critical measure for this task (including both mammal and bird data to avoid losing half of the data) and the significant correlation and the similar no go effects suggested that the processes in the bird and mammal conditions were similar. Therefore the critical dependent variable, the false alarm rate (proportion of no go trials to which participants responded to) was collapsed over the bird and mammal no go trials. This false alarm rate should give an indication of the level of inhibitory control of a participant, as the higher the rate is, the more (incorrect) responses the participant made to no go trials, indicative of low inhibitory control. The reliability of this measure was satisfactory, as was the distribution (Table 4.3).

Table 4.1

Intercorrelations of Go / No Go (picture) Task Conditions

Measure	1	2	3	4
1: Go: Bird	-			
2: Go: Mammal	.77(**)	-		
3: No Go: Bird	.05	.15	-	
4: No Go: Mammal	.20(*)	.18(*)	.60(**)	-

** Correlation is significant at the 0.01 level (2-tailed).

Stop-Signal

The stop-signal task was not initially trimmed as in the data screening above, although it uses response time as a measure (1.7% of the go responses were incorrect, 41% of the stop responses were incorrect). This was in order to maximise the differences between the participants (as in Schachar et al., 2004; Aron et al., 2003), as trimming the data would remove the outermost data points of any participants who were able to successfully inhibit their responses to stop trials to a greater extent than the majority of the sample (the same applies to those participants who found it more difficult to inhibit their responses to stop trials).

The critical dependent variable then calculated was the mean response time to the go trials (correct response only) minus the mean response time to the stop trials. The mean stop signal response time (SSRT) values of the participants was similar to that found in previous literature (225ms compared with 189ms in Aron et al. (2003)). The higher the stop signal response time, the less the inhibitory control exhibited by the participant. The reliability of this measure was excellent (Table 4.3).

The distribution of SSRT was extremely non-normal (Table 4.3). In order to normalise the distribution the times above three standard deviations were replaced by the highest value below three standard deviations plus one (for the lowest above three standard deviations, plus two for the second lowest, etc.). This was done as described above in three waves – twice for values above three standard deviations, and once for values below three standard deviations (the mean SSRT after this trimming was 212ms). These procedures are as described in Tabachnick and Fidell (2001). This resulted in the distribution being reasonably normal (Table 4.4).

Cued Recall

As the data analysed for the cued recall task were the number of correct trials, they were not trimmed (9.5% of the responses were incorrect). The two trial types analysed in the cued recall task were control and interference trials. In both trials participants were cued to recall a target word from a list (the second of two). In interference trial a foil word was also present (in the first list of the two). The first list of words was always read aloud, and the second set was always read silently. The performance of the participants was analysed with a repeated-measures ANOVA (correct control v correct interference). Before the analysis was carried out, missing values for two participants[1] on task were estimated through imputation and regression estimation procedures. The result of the estimations from these two procedures did not differ significantly, so the estimates from the imputation method using the program NORM (Schafer, 1999) were used.

[1] These participants failed to complete the cued recall task due to time constraints (arrived late to session).

Participants were more accurate in the control condition than in the interference condition ($F_{(1, 148)}$ = 220.32, $p \leq 0.01$, $\eta_p^2 = 0.60$; control = 10.13 > interference = 6.75). This effect is probably due to the effect of the foil word in the interference trials affecting recall of the target word, as expected. The critical dependent variable was calculated as the difference between the number of correct control trials and the number of correct interference trials. The mixed modality of the presentation and distracter task were common to both trials, so this dependent variable should remove any contribution from that. The dependent variable should therefore only measure the level of interference caused by the foil word in recalling the target word, interference which should be mediated by inhibitory control. The distribution of the critical dependent measure was normal (Table 4.3), so no transformations were required. However, the reliability calculated for this difference measure was too low to be used in a structural equation modelling analysis (Table 4.3). Therefore an alternate critical measure was used. Implementing the regression method (as in Friedman & Miyake, 2004), the component scores of the measure (the proportion of correct interference trials and the proportion of correct control trials), which had reasonable reliability (see Table 4.3) were used (the distribution of the component scores were also satisfactory). In the modelling stage, an additional latent variable that underlay both the correct control trial measure and the correct interference trial measure was included. This allows the common variance of the two component scores (interference due to the mixed modality of presentation and the distracter task) to be factored out, leaving only the interference caused by the foil word in the interference trial measure (therefore only the proactive interference or cognitive inhibition effect which is of interest)[2].

Theory of Mind tasks

Keysar

For the response time analyses, the data were trimmed by condition for each participant individually, looking at correct responses only (12.5% were incorrect responses to the competitor item, 1.4% were responses to another object). Response time values that were more than three standard deviations

[2] An alternative method of factoring out the common variance is shown in Appendix B. The SEM modelling gave similar results using either method.

away from the condition mean for a participant were replaced by the cut-off value (of three standard deviations from the condition mean). The data were analysed using a 2 x 2 repeated measures ANOVA, trial type (control v experimental) and condition (ambiguous v relational). Response time was looked at first, with correct responses only used. There was no effect of trial type ($F_{(1, 143)} = 0.75$, $p = 0.39$, $\eta_p^2 = 0.01$), with the response times to control and experimental trials being comparable. There was an effect of condition ($F_{(1, 143)} = 686.24$, $p \leq 0.01$, $\eta_p^2 = 0.60$), with the response time to ambiguous trials being significantly faster than to relational trials (ambiguous = 2849.84ms < Relational = 3295.67ms).

There was a significant interaction between trial type and condition ($F_{(1, 143)} = 7.17$, $p \leq 0.01$, $\eta_p^2 = 0.05$), that was investigated further with separate 2-way ANOVAs.

For the ambiguous trials there was a marginal difference between control and experimental conditions ($F_{(1, 150)} = 2.75$, $p = 0.10$, $\eta_p^2 = 0.02$), with the response time to control trials being slightly faster than to experimental trials, and the opposite pattern was shown for relational trials (a marginal difference between control and experimental conditions: $F_{(1, 143)} = 3.56$, $p = 0.06$, $\eta_p^2 = 0.02$).

In the control condition there was a significant difference in trial type ($F_{(1, 150)} = 198.90$, $p \leq 0.01$, $\eta_p^2 = 0.57$), with the response time to ambiguous trials being faster than the response time to relational trials. In the experimental condition, there was also a significant difference in trial type ($F_{(1, 143)} = 68.28$, $p \leq 0.01$, $\eta_p^2 = 0.32$), again with the response time to the ambiguous trials being faster than the response time to the relational trials. These differences can be seen in Figure 4.5. These findings, compared against the error findings described below, show no indication of a speed-accuracy trade-off.

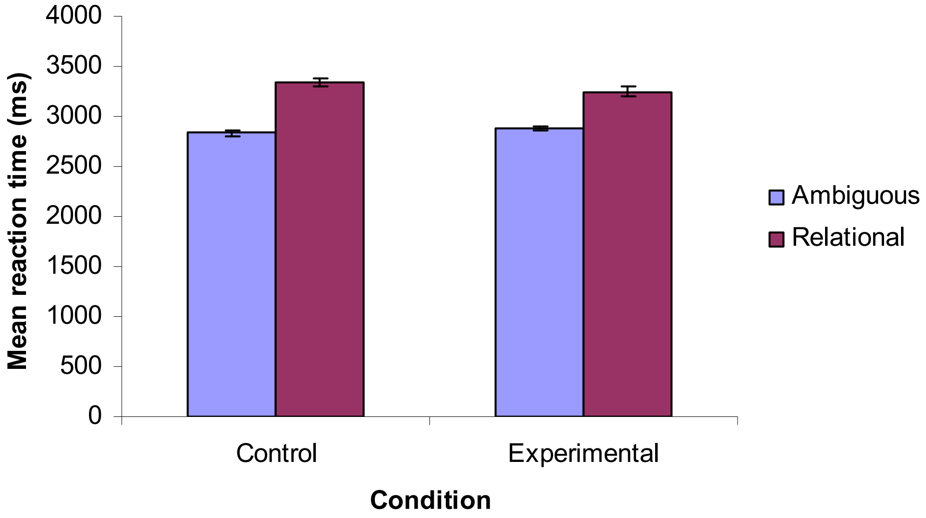

Figure 4.5: Mean response times (and standard error) in Keysar task by condition and trial type

The error rate was then examined with a series of t-tests, as no errors made in the control conditions (error data were not trimmed).

A one-sample t-test (with a theoretical value of zero) showed that significantly more errors than zero were made in the experimental condition (t (149) =13.90, $p \leq 0.01$, with a mean difference of 4.03). A paired-sample t-test showed there was also an effect of condition in the experimental trials (t (149) = 9.28, $p \leq 0.01$), with significantly more errors in the relational condition than in the ambiguous condition (ambiguous = 1.21 < relational = 2.82).

For the ambiguous trials there were significantly more errors than zero (t (149) = 12.25, $p \leq 0.01$, with a mean difference of 1.21). There were significantly more errors than zero in the relational trials (t (149) = 12.97, $p \leq 0.01$, with a mean difference of 2.82). These differences can be seen in Figure 4.6.

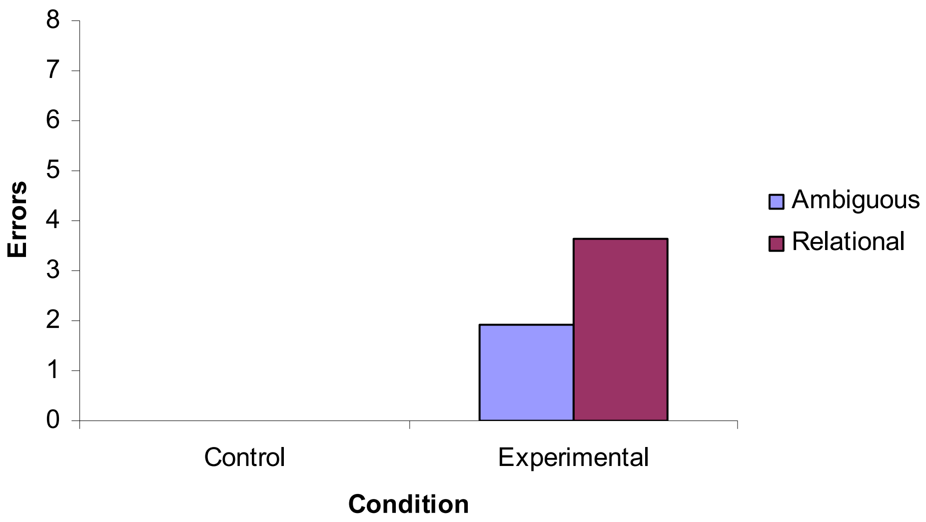

Figure 4.6: Mean number of errors (and standard error) in Keysar task by condition and trial type

The control condition was expected to have no errors and a faster response time due to there being no competing item for the item description given by the instructor. The relational trials were slower and resulted in more errors than the ambiguous trials. This may be due to there being more items that the participant is cued to in the relational trials (for example in the experimental grid where the critical instruction is 'move the small ball…', there are three different sized balls present) compared to in the ambiguous trials (where in an experimental grid, where the critical instruction is 'move the mouse…', there is a computer mouse and a mouse, so there are only two potential items). The additional item that the participant must consider in relational trials may explain the increased response times, and perhaps the increased error rate.

The critical dependent variables for the Keysar task were the error rates of the relational and ambiguous trials. These were expected to measure the participants' failure to use their theory of mind. The reliability of the relational errors was satisfactory, whilst that of the ambiguous trials was adequate (Table 4.3). Both the distributions of the dependent variables were skewed (Table 4.3), and they were both square root transformed (ambiguous with a constant of one to remove negative values). This resulted in adequately normal distributions for both dependent variables (Table 4.4).

Visual Perspective

Data trimming was conducted on correct responses only on the matching trials (4.78% of the data were incorrect responses). Response times that were 2.5 standard deviations away from the mean were eliminated (2.04% of the data; this was in line with the original procedure of data cleaning in Samson, Apperly, Braithwaite & Andrews, 2007) and so were response omissions due to the timeout procedure (responses over 2000ms; 0.47% of the data). The data were analysed using a 2 x 2 repeated-measures ANOVA, with consistency (consistent v inconsistent) and perspective (self v other) as the factors. The measure first investigated was response time in each of the conditions.

There was a main effect of consistency ($F_{(1, 153)} = 324.16$, $p \leq 0.01$, $\eta_p^2 = 0.68$), with the response time in the inconsistent condition significantly higher than that in the consistent condition (consistent = 628.49ms < inconsistent = 724.42ms). There was no effect of perspective ($F_{(1, 153)} = 2.02$, $p = 0.16$, $\eta_p^2 = 0.01$). There was a significant interaction between consistency and perspective ($F_{(1, 153)} = 60.15$, $p \leq 0.001$, $\eta_p^2 = 0.28$) that was investigated further using separate 2-way ANOVAs.
There was a significant difference between the consistent and inconsistent conditions in the other perspective condition ($F_{(1, 153)} = 274.66$, $p \leq 0.\ 01$, $\eta_p^2 = 0.64$), with the inconsistent condition being significantly slower in response times compared to the consistent condition. For the self perspective condition, there was also a significant difference between consistent and inconsistent conditions ($F_{(1, 153)} = 122.99$, $p \leq 0.01$, $\eta_p^2 = 0.45$), again with the inconsistent condition significantly slower in response time compared to the consistent condition.

In the consistent condition, the other perspective trials were significantly faster than the self perspective trials ($F_{(1, 153)} = 61.56$, $p \leq 0.01$, $\eta_p^2 = 0.29$). In the inconsistent condition, the opposite pattern was shown, and the self perspective trials were significantly faster than the other perspective trials ($F_{(1, 153)} = 8.98$, $p \leq 0.01$, $\eta_p^2 = 0.055$). The differences in effect size can be seen in Figure 4.7.

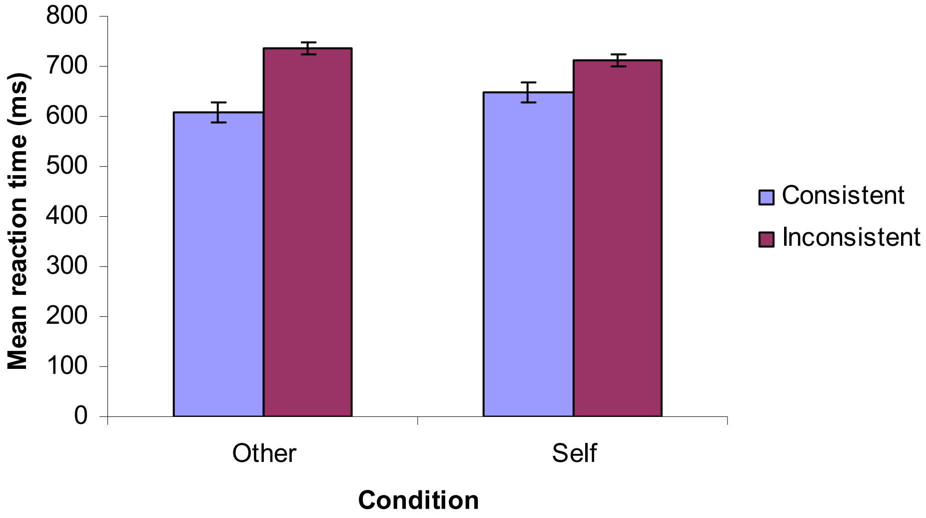

Figure 4.7: Visual perspective mean response times (and standard error) by condition and trial

The errors (not trimmed) in each condition were examined using an identical 2 x 2 repeated measures ANOVA. There was a main effect of consistency ($F_{(1, 153)} = 192.52$, $p \leq 0.01$, $\eta_p^2 = 0.56$), with more errors in the inconsistent condition than in the consistent condition (consistent = 0.53 < inconsistent = 2.20). There was again no effect of perspective ($F_{(1, 153)} = 0.68$, $p = 0.41$, $\eta_p^2 = 0.00$).

There was a significant interaction between consistency and perspective ($F_{(1, 153)} = 11.30$, $p \leq 0.01$, $\eta_p^2 = 0.07$) that was investigated further using separate 2-way ANOVAs.

For other perspective trials there was a significant difference between consistent and inconsistent conditions ($F_{(1, 153)} = 169.33$, $p \leq 0.01$, $\eta_p^2 = 0.53$), with more errors in the inconsistent condition. For the self perspective trials there was also a significant difference between consistent and inconsistent conditions ($F_{(1, 153)} = 73.39$, $p \leq 0.01$, $\eta_p^2 = 0.32$), again with more errors in the inconsistent condition. Mirroring the response time analyses, the consistent condition showed significantly more errors in the self perspective trials as compared to the other perspective trials ($F_{(1, 153)} = 7.72$, $p \leq 0.01$, $\eta_p^2 = 0.05$). The inconsistent condition for errors also showed the same pattern as that for the response times, with significantly more errors in the other perspective trials than in the self perspective trials ($F_{(1, 153)} = 5.05$, $p = 0.03$, $\eta_p^2 = 0.03$). These effects and interactions can be seen in Figure 4.8.

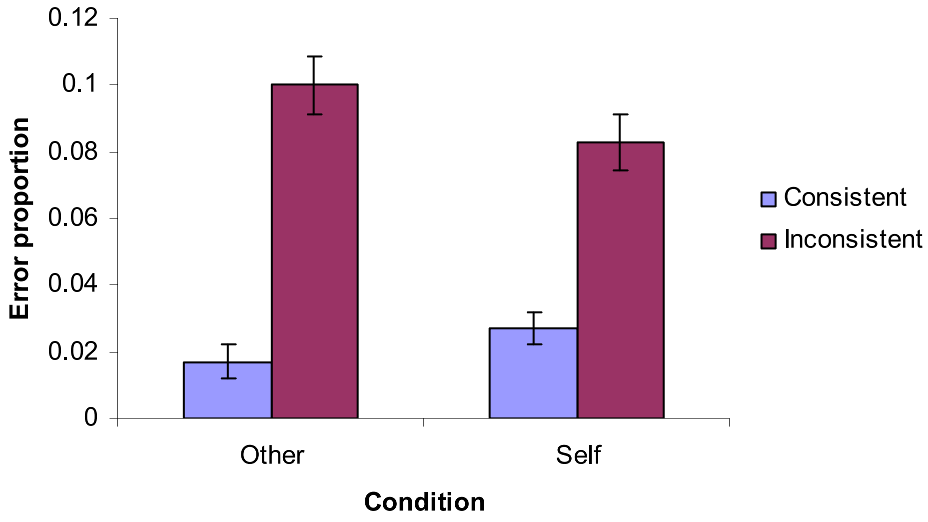

Figure 4.8: Visual perspective error proportions (and standard error) by condition and trial

There was no difference in either response time or error rate between the participants taking their own perspective (self condition) or taking the avatar's perspective (other condition), indicating that in general there was no difficulty in taking one perspective over another. Other perspective trials show higher response times and error rates than self perspective trials, possibly due to greater interference of the self perspective in the inconsistent trials only.

The critical dependent variables for the task were calculated as the differences between the inconsistent and consistent mean response times for other and self trials separately. These were taken to be measures of the interference caused by the alternate perspective when focusing on the given perspective (any common process to the consistent and inconsistent trials would be eliminated, leaving the remaining response time as a measure of interference). For this reason the difference between inconsistent and consistent trials for the other condition was termed egocentric interference (target perspective was the avatar perspective, the interference from self perspective), and the difference for the self trials was termed altercentric interference (the target perspective was the self perspective, the interference from avatar perspective). The reliability of the egocentric interference measure was satisfactory, and that of the altercentric interference measure was adequate (Table 4.3).

The distribution of the egocentric interference effect was non-normal (Table 4.3), and was square-root transformed (with a constant of 60.89 to remove negative values), resulting in a relatively normal distribution (Table 4.4). The distribution of the altercentric interference effect was relatively normal, so was not transformed (Table 4.3).

Final data screening

After the initial data screening measures for each individual task, and once the critical dependent variables had been calculated, all pairwise plots were examined for nonlinearity and heteroscedasticity. These were all satisfactory. Table 4.2 shows the initial descriptive statistics for the critical dependent variables of each task used in the individual differences model. Table 4.3 shows the initial distribution statistics for the critical dependent variables of each task, together with outlying cases. Tasks were transformed as necessary (as detailed in the individual task summaries).

Table 4.2

Descriptive Statistics for the Measures Used in the Individual Differences Model (with condition comparisons for Go / No Go tasks)

Measure	M	SD	Min	Max
Cued Recall (correct)				
Control	10.13	3.47	0	18
Interference	6.74	3.30	0	15
Simon interference effect (ms)	114.43	58.03	7.10	343.48
Shape-Matching interference effect (ms)	405.96	399.60	-406	3288.23
Go / No Go (FAR)				
Go trials	0.06	0.07	0	0.71
No Go trials	0.27	0.14	0.01	0.82
Go / No Go (picture) (FAR)				
Go Bird	0.24	0.15	0.03	0.89
Go Animal	0.17	0.14	0.01	0.93
No Go Bird	0.44	0.21	0	1
No Go Animal	0.39	0.24	0	1
Stop-Signal (SSRT)	225.72	244.86	-277.94	1721.11
Keysar (errors)				
Ambiguous	1.18	1.21	0	5
Relational	2.75	2.7	0	8
Visual Perspective interference effect (ms)				
Egocentric	128.82	96.46	-59.89	482.14
Altercentric	63.05	70.55	-105.94	295.06

Table 4.3

Initial Distribution Statistics

Task	Shapiro-Wilk	Skewness (<2)	Kurtosis (<3)	Outliers (case)	Reliability
Cued Recall (Difference)	NS	0.73	-0.38	-	0.12
Cued Recall (interference)	Significant	1.07	-0.99	-	0.66
Cued Recall (control)	NS	0.18	-0.43	3	0.71
Simon	Significant	3.75	2.29	15	0.92
SM	Significant	20.17	56.06	95, 96, 138	0.63
GNG	Significant	4.96	5.03	135, 137	0.94
GNG_P	NS	1.79	-0.53	-	0.75
SS*	Significant	-1.17	5.18	8, 16, 26 39, 71, 79, 89, 109, 137, 148	0.99
Keysar (Amb.)	Significant	4.05	-0.71	133, 149	0.53
Keysar (Rel.)	Significant	3.16	-2.73		0.85
Visual Perspective (egocentric interference)	Significant	5.49	3.75	93, 98	0.64
Visual Perspective (altercentric interference)	NS	1.89	0.35	10	0.43

NB. Shapiro-Wilk = normality test, should be non-significant; Skewness and kurtosis = distribution statistics, less than 2 and 3 respectively; reliability should ideally be more than 0.7

Once the critical dependent variables were transformed to remove univariate outliers, data were then checked for multivariate outliers. One case (number 137) was identified through inspection of Mahalanobis distances. This case varied significantly from the rest of the sample on the Simon task, the stop-signal task and the go / no go task. The variance values are also shown (an assumption of structural equation modelling is that variances of the measured indicators are within a 10:1 ratio (Kline, 2005)). The initial task scores were modified as per the amendment column, resulting in the final variance values in the final column of Table 4.4, together with the distribution statistics.

Table 4.4

Distribution Statistics After Transformations:

Task	Shapiro-Wilk	Skewness (<2)	Kurtosis (<3)	Variance	Amendment	Adjusted Variance
Cued Recall (interference)	Significant	1.075	-1.041	0.027	*15	6.13
Cued Recall (control)	NS	0.16	-0.47	0.030	*15	6.77
Simon	NS	0.769	0.187	6.94	*1	6.94
SM	NS	0.563	3.159	0.10	* 10	9.28
GNG	NS	-1.151	1.159	0.02	* 17	5.82

Task	Shapiro-Wilk	Skewness (<2)	Kurtosis (<3)	Variance	Amendment	Adjusted Variance
GNG_P	NS	1.869	-0.448	0.04	* 12	5.86
SS	Significant	-1.543	5.428	12302.11	/ 35	9.69
Keysar (Amb.)	Significant	2.08	-2.29	0.159	* 8	10.16
Keysar (Rel.)	Significant	-0.53	-3.07	0.908	* 3	8.17
Visual Perspective (egocentric interference)	Significant	0.035	3.33	12.485	* 1	12.49
Visual Perspective (altercentric interference)	NS	1.89	0.35	4921.434	/ 22	10.17

NB. variances need to be within 10:1 ratio, arrived at by multiplication or division by value in Amendment column

The critical dependent variables met all the criteria for inclusion in structural equation modelling analyses (Blunch, 2008; Kline, 2005; Tabachnick & Fidell, 2001).

5. Executive Function factor classifications

Chapter 2 established that response inhibition is proposed to underlie both go / no go tasks, the stop – signal task, and potentially also the Simon task, and the shape – matching task. Response selection may underlie all the tasks, but the extent to which this is the case is expected to vary. Cognitive inhibition is expected to be linked to the Simon, shape – matching and cued recall task. Latent variable analyses will allow the confirmation or refutation of these potential subdivisions.

Potential factors and models

As described in Chapter 2, the go / no go tasks are both expected to rely more on response selection than response inhibition, but the stop – signal task may rely on both to a more equal extent. The remaining tasks are less well established executive function tasks, and so the possible layout of their core factors is less clear cut. The fact that response selection is expected to be a factor in all of the tasks may mean that it is less distinguishable from the other two proposed factors, as the tasks that those factors tap are more independent. Using structural equation modelling will allow the elucidation of this structure, and provide evidence for the diverse or distinct nature of inhibition factors in executive function.

Another potential construct that may be present in the tasks but that will not be assessed directly by this model is working memory. The cued recall and go / no go (picture) tasks may rely on working memory as well as inhibition factors, but the dependent variables are aimed towards measuring inhibitory control only. Unexplained variance in the model (as denoted by any covariance between error terms of measured task indicators) may be attributable to working memory.

The first model tested was the simplest one factor model. As the most parsimonious model this would be the optimum choice if more complex models did not have significantly better fits. The response and cognitive inhibition two factor model was then tested. This model consisted of the go / no go tasks and the stop-signal task loading on the response inhibition latent variable (as these are the established response inhibition tasks), and the cued recall, Simon and shape-matching tasks loading on the cognitive inhibition latent variable (as in Chapter 2, these tasks all require some level of cognitive inhibition, cognitive interference or resistance to proactive interference).

A potential two factor model of response inhibition and response selection was also analysed. This alternate classification resulted in tasks loading on different latent variables than they did in the previous model (some moved from response inhibition to response selection, some from cognitive inhibition to response inhibition). The tasks loading on the response selection latent variable were proposed to tap that factor above and beyond any other construct (these were the go / no go tasks and cued recall task). The other tasks (stop-signal, Simon and shape-matching tasks) were considered to tap response inhibition when response selection was the other latent variable. This was because even though tasks were designed to tap only one construct as much as possible, they almost certainly tapped several contrasting constructs (see Chapter 2). This meant that seemingly incompatible models could be tested. Both models were allowed to be adjusted, dependent on the modification statistics. In all cases these amendments (adding or removing paths from measures to latent variables; redefinition of latent variables) were informed by theoretical considerations. The dependent variables for the inhibitory tasks are listed below in Table 5.1.

Model statistics

The program AMOS (Arbuckle, 2006) was used to calculate maximum likelihood estimation (based on the covariance matrix of the critical measures). Several different model fit statistics were used to evaluate the structural and factor models. The chi-square statistic is the most commonly used fit statistic (CMIN; which is a ‘badness of fit’ statistic). This measures the differences between the covariances in the experimental model and those in the observed data. If the experimental model has similar covariances to the observed values, then the chi-square statistic will be small, indicating no significant difference between observed and predicted covariances. The comparative fit index (CFI) which compares the experimental model with a baseline independence model with zero covariances was also included. CFI values of close to 1.0 (and above 0.9) are indicative of good fit, as this means that the model is better than a baseline model of no covariances (a low value indicates the current model is no better than a zero covariance model). The root mean square error of approximation (RMSEA) is a statistic which corrects for model complexity. RMSEA provides a lower and higher value bounding the central value. A lower bound value of less than 0.05 suggests that the directional null hypothesis (that the experimental model has close approximate fit in the population) can not be rejected. A higher bound value that does not exceed a cut-off value that indicates poor fit (for example 0.10) means that the null hypothesis that the fit of the experimental model in the population is as bad or worse can be rejected. RMSEA therefore tests the hypotheses of good approximate fit and of poor approximate fit. An incremental fit index, the Bentler-Bonett normed fit index (NFI) was also used. NFI values of over 0.9 indicate a good fitting model, again as compared to zero meaning the model is the same as a baseline zero covariance model. The Akaike information criterion index was used to compare non-hierarchical models (models that are not nested in one another). The Akaike information criterion (AIC) statistic uses an information theory approach to data analysis that combines estimation and model selection under a single conceptual framework (Kline, 2005). It is a predictive fit index (but is also parsimony-adjusted to favour simpler models). The model with relatively better fit and fewer parameters compared to other models is more likely to be replicable using different samples, and this model will have the lowest AIC value, and so be preferred.

Different models were tested (as detailed below) on theoretical grounds, and were compared using chi-square difference tests (calculated by AMOS if they were nested models). This test indicated whether removing or adding a path to a model (reducing or increasing complexity) significantly affected the model fit (by comparing the chi-square values of the models). If, when removing a path, the chi-square difference was not significant, then the path removed was not integral to the model and so did not affect the model fit. If, when adding a path, the chi-square difference was significant, the path added significantly improved the model fit. The standardised residual covariance matrix was used to see if there were any relationships between the inhibitory tasks that were not explained or accounted for by the (current) model. Paths would only be added or removed if there were strong theoretical grounds for doing so. All analyses used an alpha level of 0.05.

Descriptive statistics

Table 5.1

Dependent Variables for Inhibitory Tasks

Task	Dependent variable
Simon	Congruent trial RT – Incongruent trial RT (correct only)
Shape Matching	Distracter present, No Match trial RT – No Distracter, Match trial RT (correct only)
Cued Recall	Proportion of correct interference trials (shared effect with control trials factored out).
Go / No Go	False Alarm Rate of no go trials (proportion of errors in no go trials)
Go / No Go (picture)	False Alarm Rate of no go trials (proportion of errors in no go trials)
Stop Signal	Stop Signal Reaction Time (SSRT; Go trial RT (correct only) – Stop trial RT)

An initial correlation matrix of the inhibition tasks is shown below (after data screening, transformation and variance adjustment) in Table 5.2. The correlations give an indication of possible task groupings. As the matrix shows, there are significant correlations between the some of the proposed response inhibition tasks (in red), but not between the cognitive inhibition tasks (apart from the cued recall tasks; in blue). There are correlations between the shape-matching, cued recall, Simon, go / no go, go / no go (picture) and stop-signal tasks. The significant correlations, albeit with low magnitudes (which is normal for the type of study; Friedman & Miyake, 2004), give some indication that there are identifiable factors in the battery of tasks.

Table 5.2

Pearson Inter-correlation Coefficients for Inhibitory Tasks[1]

Measure	1	2	3	4	5	6	7	8
1: Simon	--							
2: Shape - Matching	0.01	--						
3: Cued Recall	-0.10	-0.00	--					
4: Cued Recall (int.)	-0.01	-0.08	-0.29(**)	--				
5: Cued Recall (control)	-0.09	-0.01	0.35(**)	0.66(**)	--			
6: Go / No Go	0.16(*)	-0.04	-0.23(**)	0.05	-0.01	--		
7: Go / No Go (picture)	0.01	0.13	-0.16	-0.11	-0.23(**)	0.23(**)	--	
8: Stop-Signal	0.06	0.17(*)	0.00	-0.00	-0.02	0.17(*)	0.13	--

Note: * Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

By including a latent variable that is tapped by both the cued recall measures and represents that common variance, that common variance can be factored out and accounted for (see Chapter 4). A

[1] The numbers in the header row correspond to the numbers of the tasks in left-hand column.

path is then included from the EF latent variable to the interference measure (the alternative method of doing this is shown in Appendix B, together with the alternate EF-ToM models). The abbreviations of the tasks and arrows in the models are as follows (all error variances for the models in this chapter are shown in Appendix B):

GNG	Go / No Go task
GNG (P)	Go / No Go (picture) task
SS	Stop-signal task
Simon	Simon task
SM	Shape-matching
CR (int.)	Cued Recall interference measure
CR (cont.)	Cued Recall control measure
e	Error variances
→	Parameter (direct path)
↔	Parameter (covariance)

Executive Function factor models

Model One (inhibition)

The most parsimonious one factor model was first tested (Figure 5.1):

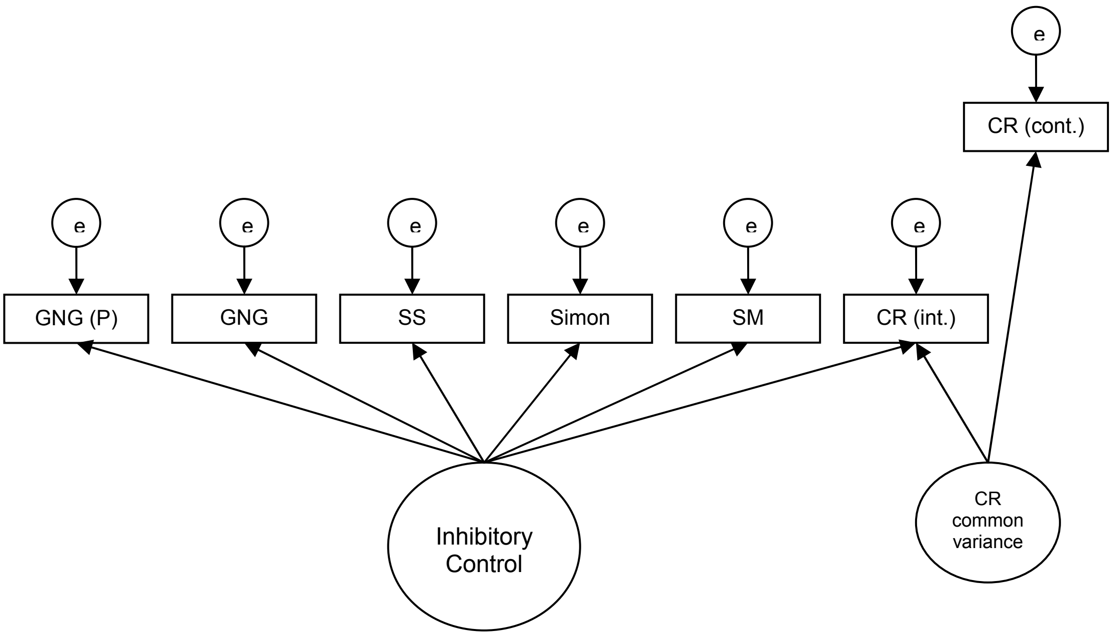

Figure 5.1: One factor inhibition model

Table 5.3 shows that all of the parameter estimates are not significantly different from zero (though the go / no go picture task approaches significance), suggesting that there is not one common factor or theoretical construct underlying all the inhibition tasks. The variance of the latent variable (of inhibition) is also not significantly different from zero. Model fit statistics for all models are shown in Table 5.10.

Table 5.3

Parameter Estimates for One Factor Inhibition Model

Parameters	Unstandardised Estimate[a]	S.E.[b]	*p*[c]	Standardised Estimate[d]
Direct effects				
Go / No Go (P)	0.98	0.52	0.06	0.35
Go / No Go	1.90	1.16	0.10	0.67
Stop Signal	1.00			0.27
CR int. (to IC)	0.46	0.31	0.14	0.16
CR int. (to res.)	1.00			0.84
CR con. (to res.)	1.00			0.81
Simon	0.65	0.43	0.13	0.22
Shape Matching	0.17	0.41	0.68	0.05
Variance				
Inhibition	0.72	1.12	0.26	
CR residual	4.36	0.64	<0.01	

[a]When the inhibition latent variable goes up by 1, the task changes by this value

[b]Approximate standard error of the estimate

[c]Whether the estimate of the task is significantly different from zero

[d]When the inhibition latent variable goes up by 1 standard deviation, the task changes by this value of standard deviations.

Model Two (response and cognitive inhibition)

A possible factor structure suggested by the literature (response and cognitive inhibition) was also analysed (Figure 5.2). There was expected to be some common variance between the two latent variables, so they were allowed to covary in the model.

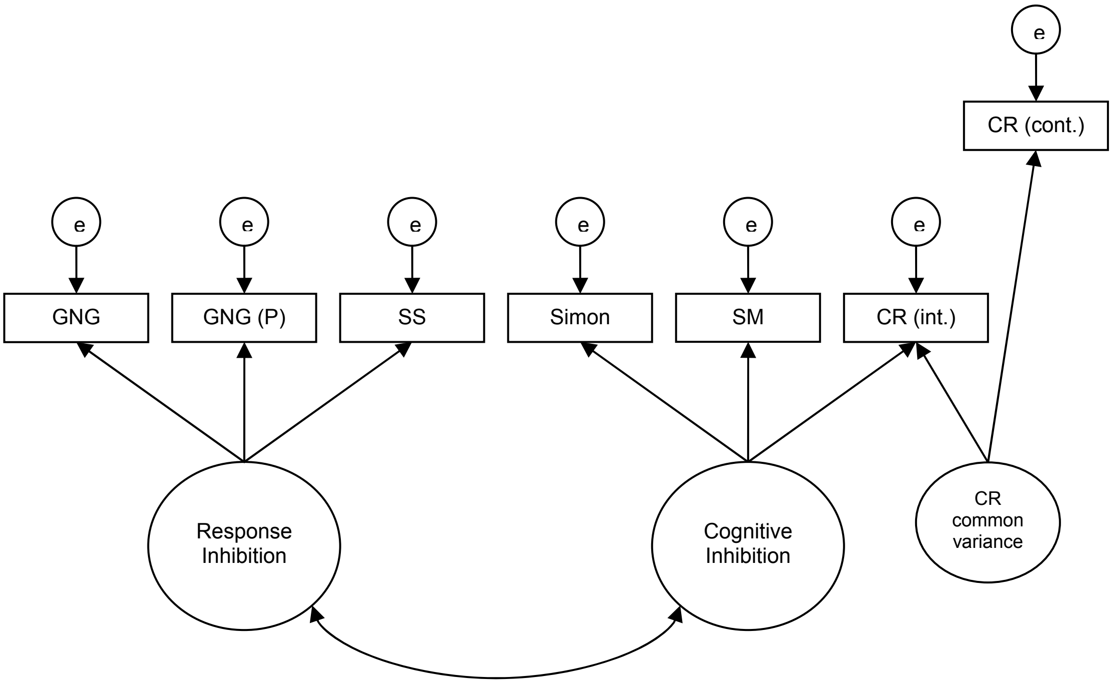

Figure 5.2: Two factor (response and cognitive inhibition) model

As Table 5.4 shows, both latent variables variances are not significantly different from zero, and the variance for the cognitive inhibition variable is extremely low. None of the task parameters to the cognitive variable or the response variable are significantly different from zero. The high correlation between the two variables (< 0.7) suggests that they are not separable variables (although the path estimate is not significantly different from zero, due to the high standard error value compared to the unstandardised estimate).

Table 5.4

Parameter Estimates for Two Factor Inhibition Model

Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
Direct effects				
Go / No Go → Response	2.11	1.40	0.13	0.71
Go / No Go (P) →Response	0.99	0.53	0.06	0.33
Stop Signal → Response	1.00			0.26
CR int. → Cognitive	0.69	0.51	0.17	0.19
CR int. → Residual	1.00			0.84
CR control → Residual	1.00			0.81
Simon → Cognitive	1.00			0.28

Table 5.4 continued

Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
Shape Matching → Cognitive	0.16	.581	0.27	0.04
Variances and covariances				
Response	0.65	0.61	0.29	
Cognitive	0.50	0.65	0.45	
Residual	4.36	0.64	<0.01	
Response ↔ Cognitive	0.43	0.34	0.20	0.76

Model Three (response inhibition and selection)

A provisional division of the tasks into response inhibition and response selection was examined next (Figure 5.3). The tasks tap different underlying constructs than in the previous model, for reasons detailed in Chapter 2 and earlier in this chapter.

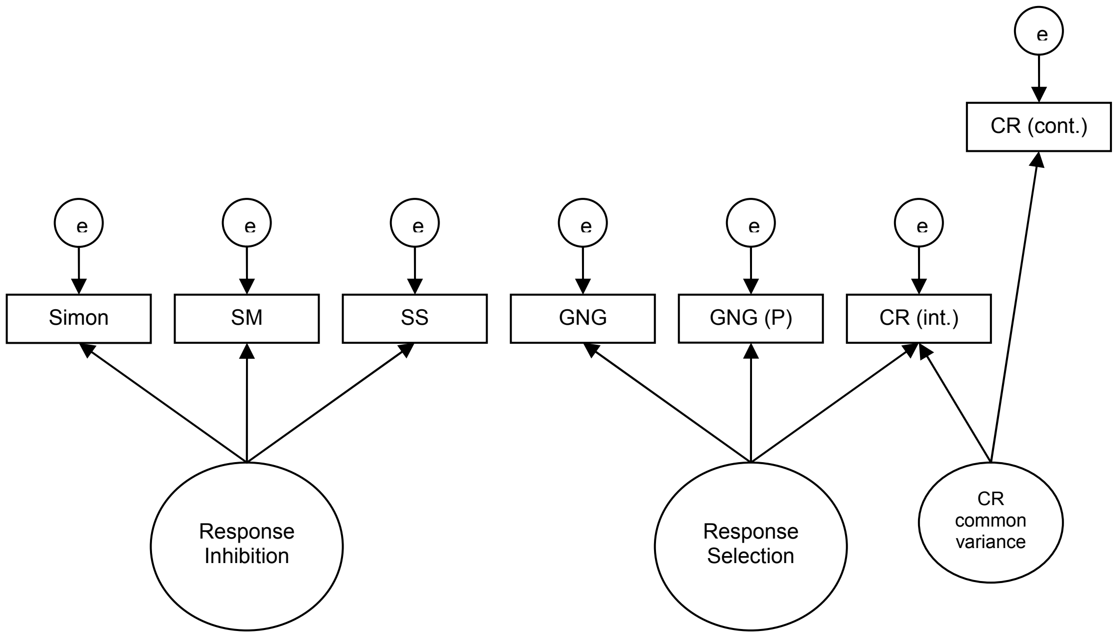

Figure 5.3: Two factor model (response inhibition and selection)

This solution shows that the variances of the two latent variables (response inhibition and response selection) are not significantly different from zero, and none of the path coefficients are significantly different from zero. Therefore the choice to test an alternate model holds (Table 5.5).

Table 5.5

Path Estimates for Response Inhibition and Selection model

Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
Direct effects				
Go / No Go → Response Selection	1.00			0.78
Go / No Go (P) →Response Selection	0.38	0.53	0.47	0.30
CR int. → Response Selection	0.19	0.27	0.47	0.15
CR int. → Residual	1.00			0.84
CR control → Residual	1.00			0.80
Stop-Signal → Response Inhibition	1.00			0.33
Simon → Response Inhibition	0.48	0.45	0.29	0.20
Shape Matching → Response Inhibition	1.52	2.14	0.48	0.51
Variances and covariances				
Response Inhibition	1.03	1.57	0.51	
Response Selection	3.54	4.87	0.47	
Residual	4.34	0.64	<0.01	

Model Four (response inhibition and selection; amended)

An alternate configuration of response inhibition and selection tasks was then chosen. As can be seen in the initial one factor model (Table 5.3), the shape matching task had the lowest unstandardised and standardised parameter estimate (as well as the highest p-value), suggesting that this task tapped a separate construct to the other tasks. Therefore a two factor model with the shape matching task loading onto one latent variable was analysed (Figure 5.4).

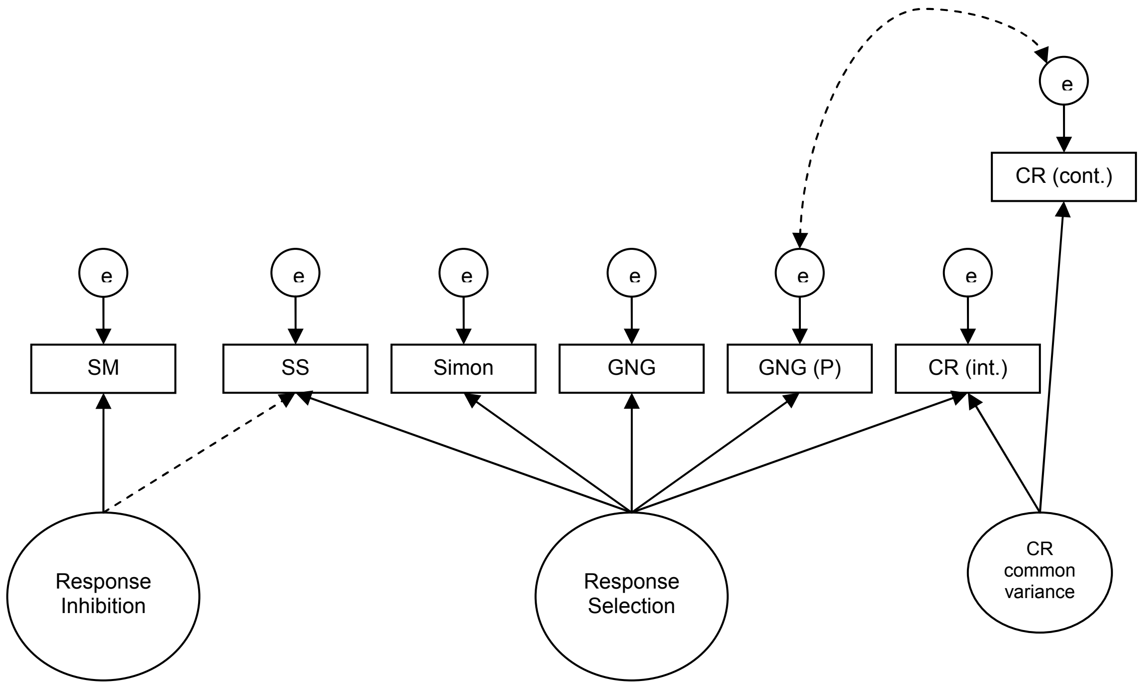

Figure 5.4: Two factor model (shape matching factor)[2]

In order to identify this model, the variance of the shape matching error term was fixed. When a latent variable has only one indicator, the unstandardised path estimate of that indicator is fixed to one. However, this still does not allow the model to be identified as there is still one unidentified parameter that needs to be constrained, in this case the error variance of the indicator. This needs to be constrained to a set value in order for the model to be identified. As the reliability of the shape-matching task is known (0.63), the error variance can be estimated using the following formula: (1 - reliability) * (standard deviation)^2 (Garson, 2008). This gives the value of the error variance as 3.53. The initial model gave the following parameter estimates, shown in Table 5.6. The parameter estimates are still relatively low, and the p-values are again not significant, but they are closer to this than the previous models. The variance of the response inhibition variable is significantly different from zero, while the variance of the response selection variable is closer to significance than any latent variable in the previous models. Therefore this was chosen as a suitable starting model for any potential theoretically informed amendments.

[2] The modifications suggested by AMOS are represented by the dashed arrows and correspond to the parameters in Table 5.7 and Table 5.9.

Table 5.6

Parameter Estimates for Initial Model (Figure 5.4)

Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
Direct effects				
Go / No Go → Response Selection	1.00			0.73
Go / No Go (P) →Response Selection	0.44	0.28	0.11	0.32
CR int. → Response Selection	0.22	0.16	0.17	0.15
CR int. → Residual	1.00			0.84
CR control → Residual	1.00			0.81
Simon → Response Selection	0.30	0.22	0.17	0.21
Stop Signal → Response Selection	0.43	0.29	0.14	0.25
Shape Matching → Response Inhibition	1.00			0.79
Variances and covariances				
Response Selection	3.10	1.94	.11	
Response Inhibition	5.69	1.07	<0.01	
Residual	4.35	0.64	<0.01	

Model 4: response inhibition to stop-signal path added

The modification indices calculated by AMOS suggested including a path from the stop – signal task to the response inhibition variable would significantly improve the fit of the model, and considering the theoretical basis for this path (that the stop – signal task requires both response inhibition and response selection), the path was added to the model. This resulted in the following set of parameter estimates (Table 5.7). Alternatives for this path include a covariance between the error terms of the shape matching and the stop – signal tasks or a covariance between the latent variables of response inhibition and response selection. These give identical values for the model fit (and equivalent parameter estimates). The path between the stop – signal and the response inhibition latent variable was chosen as it allowed the variance to be explained by the model (in the case of the alternative covariances, the variance they account for is unexplained by the model), and as it is based on the theoretical grounding that the stop-signal task taps both response inhibition and response selection. This path is shown by the straight dashed arrow in Figure 5.4.

Table 5.7

Parameter Estimates Including Path From Stop - Signal to Response Inhibition

Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
Direct effects				
Go / No Go → Response Selection	1.00			0.77
Go / No Go (P) →Response Selection	0.39	0.26	0.13	0.30
CR int. → Response Selection	0.20	0.15	0.18	0.15
CR int. → Residual	1.00			0.84
CR control. → Residual	1.00			0.80
Simon → Response Selection	0.27	0.20	0.18	0.20
Stop Signal → Response Selection	0.40	0.28	0.16	0.24
Stop Signal → Response Inhibition	0.28	0.13	0.04	0.22
Shape Matching → Response Inhibition	1.00			0.79
Variances and covariances				
Response Selection	3.44	2.23	0.12	
Response Inhibition	5.69	1.07	<0.01	
Residual	4.35	0.64	<0.01	

Model 4: go / no go error term variance constrained to zero

The error variances of the tasks were all significantly different from zero apart from that of the go / no go task. Therefore the error variance of this task was constrained to zero for the next model. This resulted in the following set of parameter estimates (Table 5.8)[3].

Table 5.8

Parameter Estimates for Figure 5.4 (Error Variance of Go / No Go Constrained to Zero)

Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
Direct effects				
Go / No Go → Response Selection	1.00			1.00
Go / No Go (P) →Response Selection	0.23	0.08	0.01	0.23
CR int. → Response Selection	0.12	0.06	0.06	0.11
CR int. → Residual	1.00			0.84
CR control → Residual	1.00			0.80
Simon → Response Selection	0.17	0.08	0.05	0.16
Stop Signal → Response Selection	0.23	0.10	0.03	0.17

[3] This was done in the reverse order to the analyses in Appendix B (here constraining the gng error variance to zero, then adding the covariance between CR int. and gng p error terms) due to negative error variances appearing when adding the covariance first.

Table 5.8 continued

Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
Stop Signal → Response Inhibition	0.29	0.13	0.03	0.22
Shape Matching → Response Inhibition	1.00			0.78
Variances and covariances				
Response Selection	5.78	0.67	<0.01	
Response Inhibition	5.69	1.07	<0.01	
Residual	4.32	0.64	<0.01	

Model 4: covariance added between cued recall and go / no go (picture)

The modification indices calculated by AMOS further suggested adding a covariance between the error terms of the cued recall control trials measure and the go / no go (picture) task. The parameter estimates for this model are below (Table 5.9). The covariance indicates that there is some unexplained variance common to the cued recall control and go / no go (picture) measure. As both tasks are plausibly the two that load most heavily on working memory, it is possible that this is the variance in common. This covariance is shown by the curved dashed arrow in Figure 5.4.

Table 5.9

Parameter Estimates for Figure 5.4 (Covariance between CR Control and GNG P Errors)

Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
Direct effects				
Go / No Go → Response Selection	1.00			0.78
Go / No Go (P) →Response Selection	0.22	0.08	0.01	0.27
CR int. → Response Selection	0.12	0.06	0.06	0.15
CR int. → Residual	1.00			0.67
CR control → Residual	1.00			
Simon → Response Selection	0.17	0.08	0.05	0.20
Stop Signal → Response Selection	0.23	0.10	0.02	0.24
Stop Signal → Response Inhibition	0.28	0.13	0.03	0.22
Shape Matching → Response Inhibition	1.00			0.79
Variances and covariances				
e3 (gng p) ↔ e7 (cr control)	-0.79	0.38	0.04	-0.22
Response Selection	5.78	0.67	<0.01	
Response Inhibition	5.69	1.07	<0.01	
Residual	4.21	0.62	<0.01	

The final four models[4] are nested within each other, and so the model fit statistics can be compared. The statistics show that adding the path from the stop-signal task to the response inhibition latent variable significantly improved the model fit (X^2 change = 4.40, df change = 1, *p* = .04). Constraining the error variance of the go / no go task (effectively removing a parameter estimate) did not significantly affect the fit of the model (X^2 change = 0.47, df change = 1, *p* = .49). Adding the covariance between the error terms of the cued recall control and go / no go (picture) tasks also significantly improved the model fit (X^2 change = 4.57, df change = 1, *p* = .03). The fit of the final model can not be compared to the one factor or response inhibition / cognitive inhibition model using a chi-square difference test, but looking at the AIC statistic shows that the preferred model is the final model (with the lowest AIC value). The final model is as Figure 5.4 with the dashed arrows included in the model and the error term of the go / no go task fixed to zero.

Table 5.10

Model Fit Statistics

Model	X^2	df	*p*	NFI	CFI	AIC	RMSEA	Low	High
One factor	21.70	14	**0.09**	0.83	**0.93**	49.70	**0.06**	**0.00**	0.11
Two factor: Response and Cognitive Inhibition	21.57	13	**0.06**	0.83	**0.92**	51.57	**0.07**	**0.00**	0.12
Two factor: Response Inhibition and Selection	24.79	14	0.04	0.81	**0.90**	52.79	**0.07**	**0.02**	0.12
Two factor (alternate response inhibition and selection)	21.78	15	**0.11**	0.83	**0.94**	47.78	**0.06**	**0.00**	0.10
Two factor (path from stop – signal to response inhibition added)	17.38	14	**0.24**	0.87	**0.96**	45.38	**0.04**	**0.00**	**0.09**
Two factor (gng error variance constrained to 0)	17.85	15	**0.27**	0.86	**0.97**	43.85	**0.04**	**0.00**	**0.09**
Two factor (covariance between CR int. and go / no go (picture) error terms)	13.28	14	**0.51**	**0.90**	**1.00**	**41.28**	**0.00**	**0.00**	**0.08**

Chi-square values that are not significant (α = 0.05) indicate a reasonable fit to the data. Values of NFI over 0.9 indicate a reasonable fit to the data. Values of CFI close to 1.0 indicate a good fit to the data. Values of RMSEA that have a lower bound less than 0.05 and a higher bound less than 0.10 show good approximate fit (and do not show poor approximate fit). The lower the AIC value, the more replicable the model (and the better the model fit). Values highlighted in bold meet the statistical criteria.

[4] The first of which is Figure 5.4, without the dashed arrows; the second is with the path from response inhibition to the stop-signal task added; the third is with the error variance of the go / no go task fixed to zero; the fourth is with the covariance between the go / no go picture and cued recall (control) error terms added.

Discussion

One factor model

The inhibitory control tasks were initially analysed as the measured indicators of a one factor model. This was the most parsimonious model, so if this provided a satisfactory fit to the data there was no requirement to analyse any further, more complex, models. The overall fit of the one factor model was satisfactory, but only the go / no go (picture) measure path coefficient approached being significantly different from zero, meaning that the model was poor overall. The following two factor models and their task classifications are shown in Figure 5.5. This figure illustrates the task groupings according to alternative accounts and the interpretations of the variance coming from each task according to each account.

Response inhibition and cognitive inhibition

The literature also suggested that there were two factors that could be present, with tasks requiring either response inhibition or cognitive inhibition. As the two factors were anticipated to have some common variance, they were allowed to covary in the model. When the model was analysed, neither the cognitive inhibition factor variance or response inhibition factor variance were significantly different from zero, and the path coefficients from the tasks to the cognitive inhibition factor were also not significantly different from zero. Only the go / no go (picture) task path estimate approached significance on the response inhibition factor. The covariance between the two latent variables was not significantly different from zero, but the standardised value was above 0.7, suggesting that the two variables were not separable (Kline, 2005). The interpretation of these statistics suggests that the classification of the inhibitory control tasks into response inhibition (go no / go, go / no go picture, stop – signal) and cognitive inhibition (cued recall, shape – matching, Simon) is not supported by the data in this study. This does not follow the general classifications of inhibitory control tasks suggested by Dempster (1993), Harnishfeger (1995) or Nigg (2000), who all proposed a distinction between interference control, cognitive inhibition and response, or behavioural, inhibition. Examining the statistics suggests that the two factor model of response and cognitive inhibition is no better a fit to the data than the one factor model, and considering the added complexity of that model, the more parsimonious one factor model should be chosen, as indicated by the AIC values.

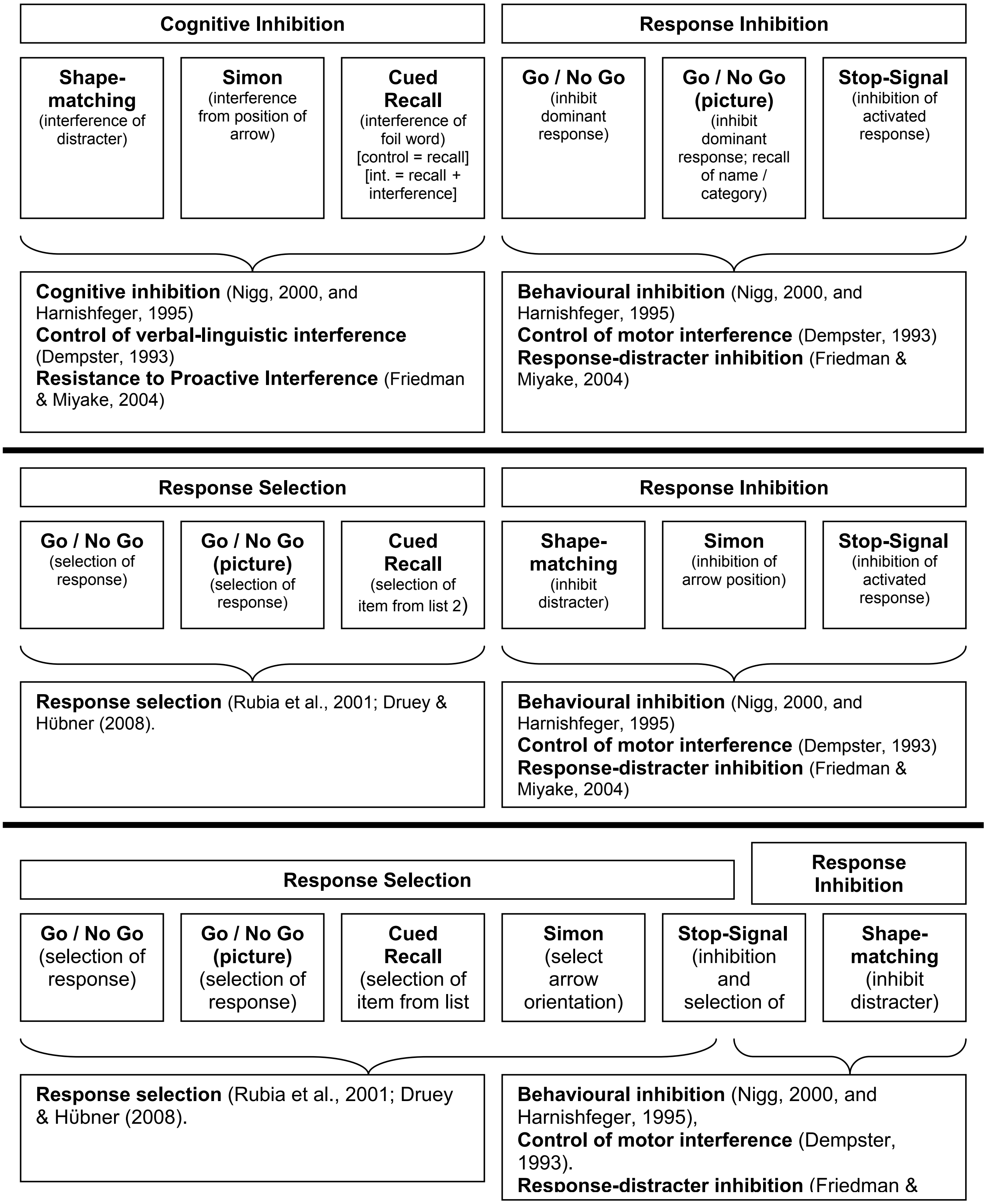

Figure 5.5: Potential factor classifications and interpretations of task variance

Response inhibition and response selection

As noted, the distinction made between response inhibition and cognitive inhibition is not supported by the data from this sample. There has been evidence suggesting that within the classic tasks that tap response inhibition (go / no go and stop – signal) there are subdivisions of the resources required (Rubia et al., 2001). The go / no go task is said to require response selection, in that the stimuli presented to the participant are categorical and are known to them prior to the commencement of the task. Therefore the participant can select their response on the basis of what is presented on the screen. There is still an element of response inhibition in that the dominant response is to respond to the trial, as out of the 26 letters that can be presented as a trial, only one has the no go response. The stop – signal task on the other hand, requires response inhibition. This is due to every trial initially being presented as a go trial, and only becoming a stop trial on the (possible) presentation of a tone a few hundred milliseconds after the letter is shown. For a stop trial the participant will therefore have to stop an activated go response, so requiring response inhibition. There is an element of response selection in that there are two letters that can be presented (either ‘O’ or ‘X’), so the participant does need to select their response on that categorical basis. The classification of the other inhibitory tasks on this basis is also possible.

Response selection may underlie all of the inhibitory control tasks, but the extent to which a task depends on it as a resource was expected to vary. The stop – signal task was proposed to load on the response inhibition latent variable, as were the Simon task and the shape – matching task, whilst the go / no go tasks and the cued recall task were proposed to load on the response selection latent variable (see Figure 5.5). The Simon task was expected to load on the response inhibition latent variable as the dominant (and learned) response is to the position of the arrow, rather than the orientation. Therefore to respond to the arrow orientation the (dominant) response to the arrow position must be inhibited (at the point of motor response). Alternatively, any interference between position and orientation could be resolved at an earlier point (which was then initially classified as requiring cognitive inhibition rather than response inhibition) but that underlying process would be identical to that of response inhibition. The shape-matching task measure was the difference between the response time to the condition in which the distracter shape was present and matched the target shape and the condition in which there was no distracter shape and the green shape matched the target shape. The difference between the two conditions in terms of processing the correct response is being able to inhibit any response to the distracter shape matching the target shape. The process of matching the green shape and the target shape is the same in both conditions. Therefore the shape-matching task dependent variable measures the ability of the participant to inhibit the processing of the distracter shape, which could either require response / behavioural inhibition in its classical definition (stop the active response to the distracter shape at the end of the process), or could require dealing with the interference between the distracter and green shapes earlier in the process, using the same underlying ability of response inhibition.

For either of these tasks, response selection could also be involved in the choice of which dimension / shape to focus on in terms of processing (orientation versus position for the Simon task; distracter shape v green shape for shape-matching task), though the type of measure used for the shape-matching task would suggest that response inhibition is more salient than response selection (as the measure focuses on the inhibiting of the distracter shape alone, so the processing or selection of the green shape is not part of the measure).

The go / no go tasks were proposed to load onto the response selection factor for the reasons listed above. The go / no go (picture) has an additional level of response selection, as the participant needs to make a selection based the class of the animal presented (bird or mammal) before then selecting whether to respond or not, based on the initial letter of the name of the animal. There will be an element of response inhibition in having to inhibit the dominant response of responding (as there are only 18 names that began with a vowel compared with 72 that began with a consonant). For the cued recall task the participant knew that the word they needed to recall would always be in the second list, and so they should have been able to select that target word over the foil word when they needed to respond. This would require response selection.

The analysis of this two factor model resulted in the latent variables variances not being significantly different from zero. None of the indicator path estimates were significantly different from zero either, and the model fit statistics suggest that this model provides a poor approximate fit to the data (this model had the worst fit statistics of all the models tested). This indicates that this classification of the tasks into those that tap either response selection or response inhibition is not supported by the current dataset.

Final model and amendments

The low path coefficient estimates of the shape – matching task in the one factor model pointed towards an alternate configuration of the inhibitory control tasks. The shape-matching task appeared to tap a different construct to the other tasks in the one factor model. In order to test this approach, the shape-matching task was used to estimate a latent variable. As this latent variable had only a single indicator, the variance of the error term of the shape-matching task was fixed (in order to estimate the path coefficient by identifying the model, in addition to fixing the unstandardised path estimate as normal). The error variance was calculated from the reliability value of the shape-matching task. The remaining tasks were loading onto the response selection latent variable[5] (see Figure 5.5). The Simon task was theorised to require response selection in order to select the dimension to respond to, rather than having to inhibit the processing of one dimension (position) in order to process the other (orientation). The stop-signal tasks requirement for response selection is less clear, but there may have been a need for the initial selection of the letter to respond with. The participants also knew what to expect (hear a tone, do not respond), so they may have had two concurrent processes that competed with each other until the point of the tone or the point of response. It is possible that response selection was required to select the process to prioritise. The shape-matching task remained on the response inhibition latent variable, as noted above.

The results of this model showed that the response inhibition latent variable's variance was significantly different from zero. The path coefficients of the tasks did not approach being significantly different from zero, suggesting that although this model was better in terms of overall fit there were still improvements that could be made. The analysis suggested adding a path from the stop-signal task to

[5] The latent variable was defined as response selection due to having the go / no go tasks loading on it. The statistics show that by the final model the tasks all do tap a common construct.

the response inhibition variable, which had some theoretical grounding, as the stop-signal task is said to require both response inhibition and response selection. Alternatives to adding a direct path between the stop-signal task and the response inhibition latent variable were adding a covariance between the error terms of the stop-signal task and shape-matching task, or adding a covariance between the two latent variables. The parameter and factor estimates were identical for all three potential choices. The direct path was chosen as this resulted in it contributing to the explained variance in the model (the other two, being covariances, represented unexplained variance). This resulted in the best fitting model statistically, as well as one that is theoretically grounded.

The modification indices also suggested adding a covariance between the error terms of the cued recall (control) task error term and the go / no go (picture) task error term. This indicates that these tasks have common variance that is not explained by the current model. These task measures have the highest demand for working memory in comparison to the other task measures in the model (none of the other tasks require the recall of information). The cued recall (control) measure is the proportion of correct control trials, which is affected by the presentation modality and the distraction task only. Therefore it would seem only to require working memory, with little interference control that would require inhibition. The go / no go (picture) task measure is the proportion of incorrect response to no go trials. This requires both inhibition (of the dominant response based on initial letter) and working memory (recall of the animal category and the recall of the name of the animal). As working memory seems to be common to both tasks, the covariance was added to the model. Adding these two paths (the stop-signal to response inhibition direct path, and the covariance) significantly improved the model fit. The error variances of the measured indicators were all significantly different from zero, except for that of the go / no go task. Therefore this error variance was fixed to zero in the final model. Removing this parameter (fixing it to zero) did not significantly affect the model fit. The inhibitory control model therefore consisted of the six tasks loading onto two separate latent variables, defined as response inhibition and response selection. Tasks loading on the response inhibition latent variable were the shape-matching and stop-signal task, and the tasks loading on the response selection latent variable were the stop-signal, go / no go, go / no go (picture), cued recall and Simon tasks.

An issue to be noted is the low path estimates of some of the measured indicators. This suggests that the amount of variance in these indicators that is explained by the underlying inhibitory factors is relatively low. These values were still significantly different from zero however, which indicates that the inhibitory factors explain a low but significant proportion of the tasks variances. The reliabilities of the tasks were all reasonable, which suggests that the measured effects were consistent throughout the duration of the tasks. A final issue is that the definitions of the latent variables are constrained by the nature of the tasks used, and are hence not definite. The issue of vague interpretations of executive functions is a recognised problem in both latent variable analysis and executive function research (Miyake et al., 2000). However, the model analyses suggest a clear factor structure. This has been interpreted in terms of the existing literature to provide a plausible basis to continue on to examine the relationship of these inhibitory factors with ToM.

The final model consists of two inhibition components, defined as response inhibition and response selection. Response inhibition underlies the shape-matching task and stop-signal task, and response selection underlies the go / no go tasks, the cued recall task, the Simon task and the stop-signal task. A covariance between the cued recall (control) task and go / no go (picture) task indicates shared unexplained variance that may be attributable to working memory. This provides a novel classification of the executive functions underlying these tasks, and does not directly support the inhibitory classifications of Nigg (2000), Dempster (1993), or Harnishfeger (1995). There is some support for the two factor model found by Friedman and Miyake (2004), though the precise definitions of the factors are different. Some of the dissimilarity could be due to the different tasks used (for example, Simon and go / no go tasks were used in the current study). The current tasks were also primarily developed for this study, whereas more established tasks were used by Friedman and Miyake (2004). This could lead to the differences between the current findings and those of earlier studies and theorists.

6. Inhibitory control and theory of mind tasks

Chapter 5 established two inhibitory components, response inhibition and response selection. The relationships between these inhibitory latent variables and ToM were then analysed using structural equation modelling.

Visual perspective task

The two dependent measures used in the model were the differences between the inconsistent and consistent response times for the avatar trials and for the self trials. Both differences give a measure of the amount of interference caused by the alternate perspective, and hence the difference between the inconsistent and consistent avatar trials was termed 'egocentric interference' and the difference between the inconsistent and consistent self trials was termed 'altercentric interference'. These two effects were proposed to correlate significantly with one another, and this proved to be the case (Table 6.1). However, as the magnitude of the correlation was relatively small, the measures were treated as single indicators of separate latent variables that were then allowed to covary. As the reliability of the measures were known (egocentric = 0.63, altercentric = 0.43), their error variance could be estimated using the following formula: (1 - reliability) * $(\text{standard deviation})^2$ (Garson, 2008). This gives the error variances of the egocentric and altercentric measures as 4.49 and 5.80 respectively.

Keysar task

The data showed that participants consistently made errors in the experimental trials that were attributable to either not being able to take the instructor's perspective into account, or not being able to use the information gained from taking the instructor's perspective into account. Results from a series of studies by Apperly et al. (submitted) indicate that the participants are not using the information gained from taking the instructor's perspective. The results from these studies, which used variations of the study used in the current model, have two potential explanations. Participants may take the instructor's perspective during or after they hear the instruction (using this on-the-fly to ignore and identify the incorrect and correct items), or they may use the time before the initial instruction for each grid to identify and rule out items that the instructor can and can not see, and then hold this information in mind whilst then listening to the instructions. Difficulties in both on-the-fly calculating of the instructor's perspective and holding in mind that perspective may explain the propensity of adults to make errors in this task, and both of these possible processes may require executive function. A third possibility is that the difficulties arise from issues in switching perspectives, rather than from having to infer, hold and use information about another perspective. This was investigated by Apperly et al. (submitted) through experiments using two instructors with different perspectives (one had the same perspective as the participant (the informed instructor), whilst the other was ignorant as in the original experiment). The instructions were given by the informed instructor half the time and the ignorant instructor half the time. The critical trials were preceded by an instruction by the same instructor (no-switch condition) or by the other instructor (switch condition). If switching perspectives (due to the instruction from the instructors) caused the errors, more errors should be made in the switching condition. The results showed that there was no main effect of switching, suggesting that participants have no difficulty in switching perspectives, and hence errors are more likely to be caused by issues in inferring, holding and using perspective information.

Within the experimental trials, there were significantly more errors made in relational trials than in the ambiguous trials (Apperly et al., submitted). The reason for this may be that the ambiguous instruction draws more attention to the perspective difference between the participant and instructor than a relational instruction. The increased salience of the perspective difference in the ambiguous trials may make the instructors perspective easier to compute on line, and easier to hold the instructors perspective in mind.

These two effects were also proposed to correlate significantly with one another due to the similar demands of having to infer the instructor's perspective, hold this in mind and then use the information from his perspective, and this proved to be the case (Table 6.1). As the size of the correlation was relatively large, the measures could be treated as indicators of a single latent variable[1]. However, due

[1] As the correlation is less than 0.7, the two measures may tap the same construct but the size of the correlation suggests that combining them to form a single measure indicator is not necessary or desirable.

to the possible differences in processing involved in ambiguous and relational trials, they were treated as single indicators of separate latent variables that were also allowed to covary. The error variance of the indicator needed to be fixed in order for the model to be identified. As the reliability of the Keysar measures are known, the error variance can be estimated using the following formula: (1 - reliability) * (standard deviation)^2 (Garson, 2008). This gives the values for the error variances of the relational measure and ambiguous measure as 1.23 and 4.77 respectively.

Table 6.1

Pearson Inter-correlation Coefficients for Theory of Mind Measures

Measure	1	2	3	4
1: Ambiguous errors (Keysar)	--			
2: Relational errors (Keysar)	0.64 (**)	--		
3: Egocentric intrusions	0.05	0.06	--	
4: Altercentric interference	-0.08	-0.04	0.22 (**)	--

Note: ** Correlation is significant at the 0.01 level (2-tailed).

As Table 6.1 shows, there are no significant correlations between the measures from the visual perspective task and the measures from the Keysar task. Both tasks are level-one perspective taking tasks, so even though one task appears to be ‘harder’ in terms of task demands (the Keysar task), it might have been expected that the pairs of tasks measures would correlate due to similar general processes. This is because both tasks require perspective taking, the maintenance of that perspective and any information contained in it, and being able to deal with any perspective interference. However, the Keysar task has a larger set of items to maintain, and also requires the participant to problem-solve by integrating perspective information with the instructions given in the task. Both of these suggest greater task demands for the Keysar task. The sets of correlation between the measures of the Keysar task and the measures of the visual perspective task are all non-significant (the magnitude of these correlations are all < 0.09), so one possibility is that these tasks are measuring different processes or abilities, perhaps within theory of mind or perhaps two different types or systems of ToM. Another possibility is that the greater task demands of the Keysar task cause the low correlation with the visual perspective task. As the Keysar task is more difficult, it may recruit different executive functions to the visual perspective task, leading to a lack of correlation.

As there is no correlation between the measures from the two tasks in the structural models they will be treated as separate. Therefore, there will be four latent variables for the four measured indicators with covariances and relationships between the ambiguous and relational error latent variables, and also between the egocentric and altercentric latent variables.

The abbreviations of the tasks in the models are as follows (EF tasks as before):

K (amb.)	Ambiguous errors in the Keysar task
K (rel.)	Relational errors in the Keysar task
VP_O	Visual perspective trials focusing on avatar perspective
VP_S	Visual perspective trials focusing on self perspective
d	Disturbances of latent variables (error terms)

Structural Equations

A two-step approach to the modelling was used (Kline, 2005), with a confirmatory factor analysis (CFA) model being estimated as the first step to check that the model was identified. This was to establish that a more parsimonious structural model would also be identified. This can be seen in appendix C. This gave an adequate fit to the data (Table 6.6). The structural (SR) model was identified as the second step. The error variances of the ToM latent variables are shown in Appendix B.

Saturated model (all paths)

The initial SR model retained all paths between the inhibitory factors of response inhibition and response selection and the ToM target tasks (Figure 6.1). In the initial models the relationships between the ToM latent variable pairs (Keysar ambiguous errors – relational errors; Visual perspective egocentric interference – altercentric interference) were represented by direct paths between the latent variables. This would mean that performance on one of a pair would predict performance on the other, in other words, there are similar processes in both measures. An alternative arrangement would be to have a covariance between the disturbances of the latent variable pairs. This would represent unexplained (by the model) common variance.

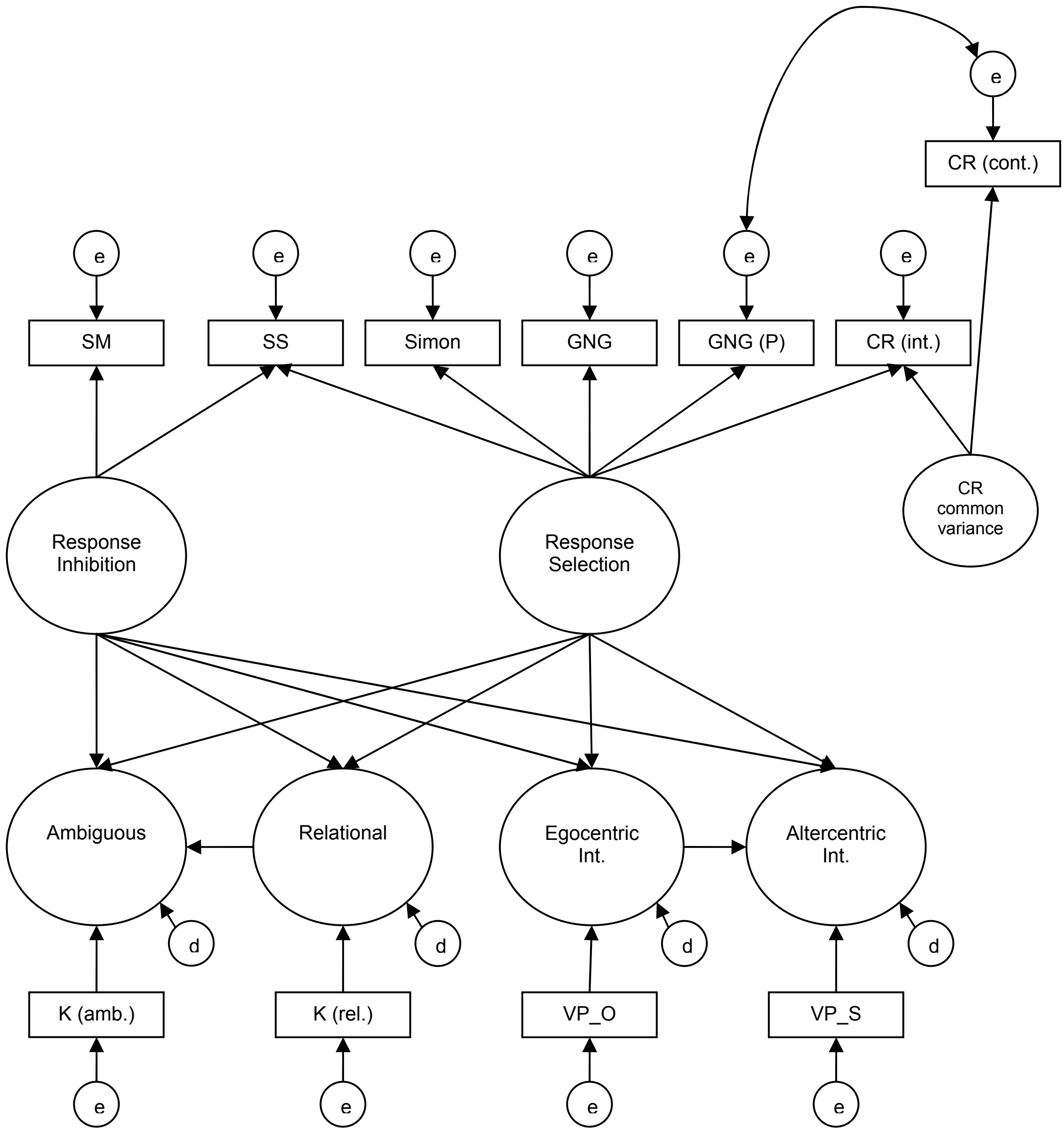

Figure 6.1: All paths from inhibitory factors

The estimates for all the parameters can be seen in Table 6.2. All the path estimates that were not significantly different from zero were set to zero in the next model. The estimates of the EF parameter estimates have the same values as in Chapter 5. The squared multiple correlation (SMC) values give an indication of the amount of variance of the latent variable that is explained by the model (cf. r^2).

Table 6.2

Parameters for All Paths Model

Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
Direct effects				
Relational ← RI	0.26	0.12	0.03	0.24
Ambiguous ← RI	-0.10	0.11	0.35	-0.11
Egocentric int. ← RI	0.45	0.15	0.01	0.38
Altercentric int. ← RI	0.16	0.15	0.29	0.19
Relational ← RS	-0.01	0.01	0.89	-0.01
Ambiguous ← RS	0.01	0.08	0.87	0.02
Egocentric int. ← RS	0.18	0.12	0.12	0.16
Altercentric int. ← RS	0.05	0.11	0.62	0.06
Rel. → Amb.	0.86	0.09	<0.01	0.98[2]
Ego. Int. → Alt. Int.	0.26	0.13	0.05	0.35
Variances and covariances				
RS	5.78	0.67	<0.01	
RI	5.68	1.07	<0.01	
Residual	4.21	0.62	<0.01	
Squared Multiple Correlations (SMC)				
Relational	0.06			
Ambiguous	0.93			
Ego. Interference	0.17			
Alt. Interference	0.22			

Model 2 (significant paths only)

The remaining paths, from response inhibition to egocentric interference and from response inhibition to relational errors, were both significantly different from zero. The parameter estimates can be seen in Table 6.3, and the model itself in Figure 6.2.

[2] As this estimate is above 0.7, an interpretation is that these two latent variables are in fact the same. In order to test this, models with one latent variable for the Keysar task were tested (with ambiguous and relational errors as indicators). The statistics suggest that in the all path models, the one Keysar LV model is preferred, but in the significant path only models, the individual measure Keysar LVs are preferred (see Appendix C).

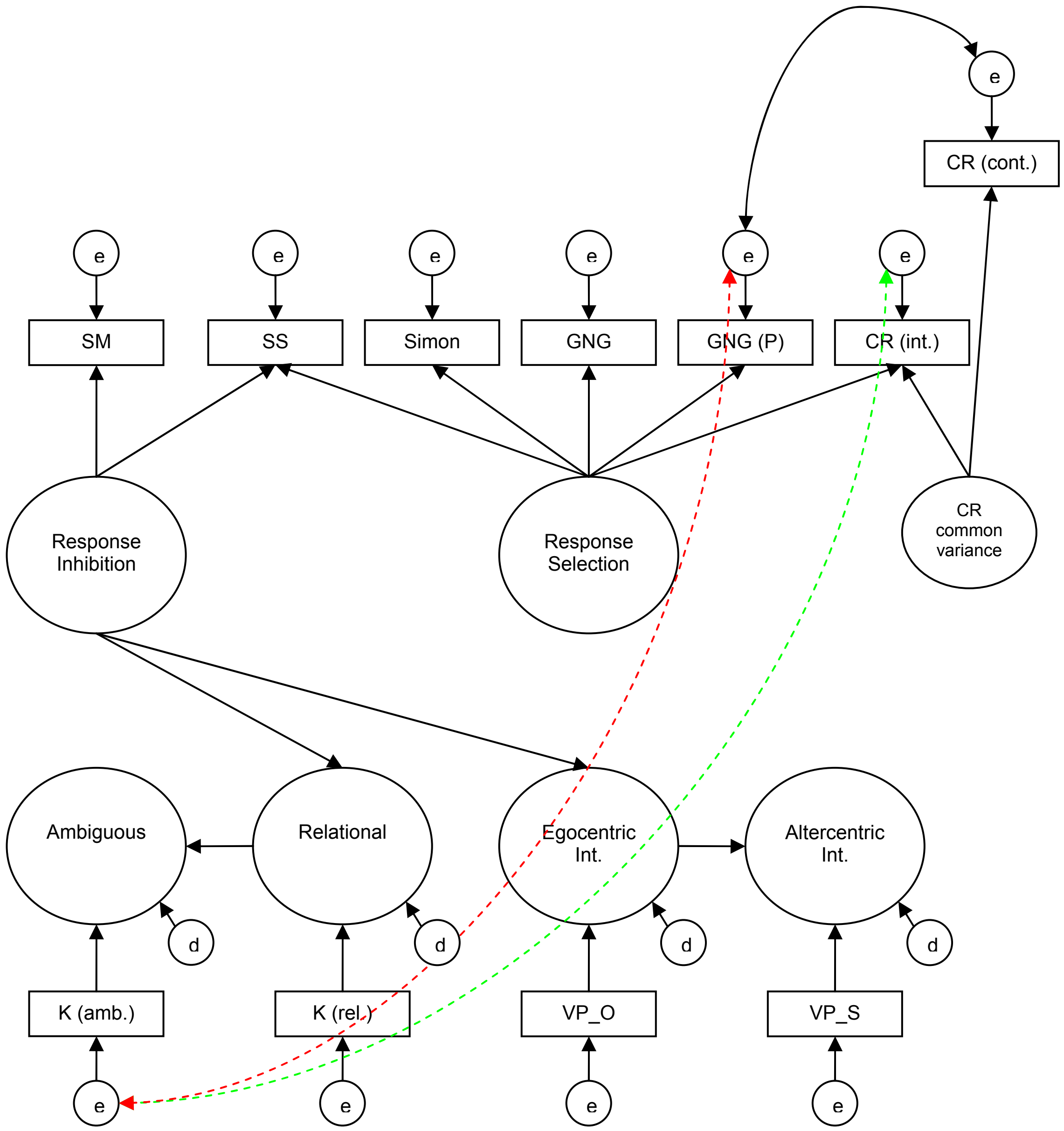

Figure 6.2: Significant paths only (final model[3])

Table 6.3

Significant Paths Only

Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
Direct effects				
Relational ← RI	0.25	0.12	0.04	0.23
Egocentric int. ← RI	0.46	0.15	<0.01	0.39
Rel. → Amb.	0.83	0.09	<0.01	0.96

[3] The final model includes the two covariances in green (Table 6.4) and red (Table 6.5)

Table 6.3 continued				
Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
Ego. → Alt.	0.33	0.11	<0.01	0.45
Variances and covariances				
RS	5.78	0.67	<0.01	
RI	5.67	1.07	<0.01	
Residual	4.21	0.62	<0.01	
Square Multiple Correlation				
Relational	0.05			
Ambiguous	0.91			
Ego. Interference	0.15			
Alt. Interference	0.21			

Model 3 (covariance between cued recall and ambiguous errors)

The modification indices suggested adding a covariance from the error term of the cued recall interference measure to the error term of the ambiguous errors task would significantly improve the model fit. As the model was designed only to measure inhibitory control as the construct of interest, the covariance suggests the presence of another construct that is unexplained by the current model (covariance in a SR model indicated shared unexplained variance between the two variables involved). It is likely that inhibitory control is not the only executive function or theoretical construct that is related to or part of ToM, so the covariance was added to the model. This covariance is shown by the dashed curved green line in Figure 6.2.

Table 6.4

Path Model with Covariance between CR and Ambiguous Errors Added

Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
Direct effects				
Relational ← RI	0.25	0.12	0.04	0.22
Egocentric int. ← RI	0.46	0.15	<0.01	0.39
Rel. → Amb.	0.79	0.08	<0.01	0.94
Ego. → Alt.	0.33	0.11	<0.01	0.45
Variances and covariances				
e CR ↔ e Amb.	-1.34	0.39	<0.01	-0.44
RS	5.78	0.67	<0.01	

Table 6.4 continued

Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
RI	5.67	1.07	<0.01	
Residual	4.18	0.61	<0.01	
Squared Multiple Correlations				
Relational	0.05			
Ambiguous	0.88			
Ego. Interference	0.15			
Alt. Interference	0.21			

Model 4 (covariance between go / no go (picture) and ambiguous errors)

The modification indices showed that adding a covariance between the go / no go (picture) measure error term and the ambiguous errors task error term would significantly improve the model fit. As the go / no go (picture) and the cued recall task (which already covaried with the ambiguous errors error term) were correlated, it was likely that this covariance represented the same unexplained variance as the previous covariance. Therefore it was added to the model. This covariance is shown by the dashed curved red line in Figure 6.2.

Table 6.5

Path Model with Covariance between GNG (P) and Ambiguous Errors Added

Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
Direct effects				
Relational ← RI	0.24	0.12	0.05	0.22
Egocentric int. ← RI	0.46	0.15	<0.01	0.39
Rel. → Amb.	0.73	0.08	<0.01	0.92
Ego. → Alt.	0.33	0.11	<0.01	0.45
Variances and covariances				
e CR ↔ e Amb.	-1.14	0.38	<0.01	-0.38
e GNG (P) ↔ e Amb.	1.24	0.47	<0.01	0.24
RS	5.78	0.67	<0.01	
RI	5.67	1.07	<0.01	
Residual	4.19	0.61	<0.01	

Table 6.5 continued

Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
Squared Multiple Correlations				
Relational	0.05			
Ambiguous	0.85			
Ego. Interference	0.15			
Alt. Interference	0.21			

At this point all the parameters included were significantly different from zero, and there were no parameters that would significantly improve the model fit that had a strong theoretical grounding. The model fits can all be seen in Table 6.6.

Table 6.6

Model fit statistics

Model	CMIN	df	*p*	NFI	CFI	AIC	RMSEA	Low	High
CFA model	61.77	38	0.01	0.78	**0.90**	117.77	**0.07**	**0.03**	**0.09**
All paths	61.91	38	0.01	0.78	0.89	115.56	**0.07**	**0.03**	**0.09**
Significant paths only	66.67	44	0.02	0.76	**0.90**	110.67	**0.06**	**0.03**	**0.09**
Sig. paths (add. cov.)*	53.60	43	**0.13**	0.81	**0.95**	99.60	**0.04**	**0.00**	**0.07**
Sig. paths (add. cov)**	46.75	42	**0.28**	0.83	**0.98**	**94.75**	**0.03**	**0.00**	**0.06**

*added covariance between error terms of cued recall interference measure and ambiguous errors measure
**added covariance between error terms of go / no go (picture) measure and ambiguous errors measure

The final model includes significant paths from the response inhibition latent variable to the egocentric interference effect, from the response inhibition latent variable to relational errors, There are also covariances from the cued recall interference measure error term to the error term of the Keysar ambiguous errors measure, and from the go / no go (picture) measure error term to the error term of the Keysar ambiguous errors measure, indicating a shared variance that is unexplained by the current inhibitory model. As these tasks are correlated, it is likely to be the same unexplained variance in both covariances. This could potentially be a different executive function such as working memory. A different battery of executive tasks could be used to investigate this potential relationship.

Discussion and follow up analyses

Structural equation model

The initial overall model was a confirmatory factor analysis model, with covariances between the two inhibitory control latent variables (response inhibition and response selection) and the four ToM latent variables (egocentric interference, altercentric interference, relational errors and ambiguous errors). There were also covariances within the pairs of ToM measures (between the egocentric and altercentric interference measures, and between the relational and ambiguous error measures)[4]. This model was identified (this step is necessary to establish that the more parsimonious structural model will also be identified, and in addition to check that the model had a reasonable fit to the data), so the structural model was tested next in which the covariances were replaced by direct paths for the structural model. The path estimates that were not significantly different from zero were removed. This resulted in direct paths from the response inhibition latent variable to the egocentric interference latent variable and to the relational error latent variable. There were also direct paths between the pairs of ToM latent variables (that replaced the covariances). The fit statistics for this model were adequate, but the modification indices suggested adding covariances from the error term of the cued recall interference measure and the error term of the go / no go (picture) to the error term of the ambiguous error latent variable. Adding covariances between error terms of indicators of endogenous and exogenous latent variables is only done when there are good theoretical grounds for doing so (it should not be done simply to improve model fit). The covariance between the cued recall control measure and go / no go (picture) error terms suggests that these tasks tap a construct not included in the current model. This is likely, due to task demands, to be working memory. As working memory has also been linked to ToM performance (Carlson & Moses, 2001) in children, it is possible that it is also related to ToM in adults. Therefore the covariances were added to allow this relationship in the model. This resulted in a good set of fit statistics, in terms of the individual path coefficients and also the overall model fit.

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[4] The value of the estimate for the path between the relational and ambiguous latent variables was $<$ 0.9, suggesting they were identical, so an alternative set of models was tested in which the relational and ambiguous measured indicators tapped one Keysar latent variable. AIC values indicated that the separate Keysar latent variables models were better than the single Keysar latent variable models when non-significant paths between the EF and ToM latent variables were removed (see appendix C).

Path from Response Inhibition latent variable to the Egocentric Interference latent variable. This path shows that the variability of participants on the response inhibition latent variable affects their variability on the egocentric interference latent variable. The model structure means that an increase in the response inhibition latent variable results in an increase in the egocentric interference latent variable. As a high score on the measured indicators of the response inhibition factor (for both the shape-matching task and the stop-signal task) is a result of greater interference (by the distracter in the shape-matching) and less inhibitory control (in the stop-signal task), the higher the factor score, the lower the ability to efficiently inhibit responses. The egocentric interference measure also increases when the interference between the perspectives is greater (a higher response time equates to lower performance). Therefore the (positive) path coefficient between the response inhibition and egocentric interference latent variables shows that the ability to inhibit responses successfully is associated with the ability to successfully deal with interference from your self perspective when attempting to process another's perspective. There is no path between the response inhibition latent variable and the altercentric interference latent variable.

The direct path between the two visual perspective latent variables could be replaced by a covariance between their error terms. This would represent a shared variance that is unexplained by the model. The direct path represents a relationship that accounts for some of the variance in the model as a whole. Changing the direction of the path between the two latent variables affects the model fit, the path estimates and the interpretation of the model. The direction in the current model is from the egocentric interference latent variable to the altercentric interference latent variable. The reasoning behind this is that as the response inhibition latent variable has a path to the egocentric latent variable, it seems more sensible to have an indirect link from the response inhibition latent variable to the altercentric interference latent variable through the egocentric interference latent variable. The interpretation of this would be that dealing with interference from the self perspective (whilst trying to process an alternate perspective) requires some response inhibition, but that dealing with interference from another's perspective whilst processing one's own does not explicitly require response inhibition.

To test this, further models were analysed to check that the path between the response inhibition latent variable and the egocentric latent variable did not mask a path between response inhibition and the altercentric latent variable. When a path was added between response inhibition and the altercentric latent variable (with the removal of the response inhibition-egocentric path), this path was significantly different from zero (Tables 4.1 and 4.3 in Appendix D). This suggests that altercentric interference also taps response inhibition. In these models the path between the interference latent variables was from altercentric to egocentric. When this path was reversed, the response inhibition – altercentric path was no longer significant (Table 4.2 in Appendix D). In order to see what would happen to the response inhibition – egocentric path in the same situation, a model was tested with a path from response inhibition to egocentric interference (with no response inhibition – altercentric path), with the path between the perspective variables from altercentric to egocentric. In this model, the response inhibition-egocentric path remained significant (Table 4.4 in Appendix D). The implication is that both egocentric and altercentric interference effects tap response inhibition, but that the stronger relationship is between response inhibition and egocentric interference. The best fitting model statistically (see Table 4.6 in Appendix D; Figure 6.2; Table 6.5) has a direct path from response inhibition to egocentric interference, and a path from egocentric to altercentric interference.

However, from a conceptual standpoint it seems more likely that response inhibition is directly required in both interference effects, most probably in dealing with any interference arising from conflict between the perspectives. Model D in Appendix D (Figure 4.4 and Table 4.5) shows this relationship, with paths from response inhibition to both interference variables. The previous models (Tables 4.1 and 4.3 in Appendix D) also suggest that altercentric interference is related to response inhibition. The relationship between the interference variables is represented by a covariance. The model fit statistics for this model (Table 4.6 in Appendix D) show that it has a similar (albeit slightly less close) fit to the data as the final model shown in Figure 6.2. The interpretation of this model is that dealing with interference from another perspective requires response inhibition (more so in the case of egocentric interference). There is also a theoretical construct that is common to both interference effects. This is not response inhibition, and may be another executive function. This model makes more sense theoretically than the current final model, but that model is better statistically. These models will be revisited in the general discussion (Chapter 9) in light of the findings from Chapters 7 and 8.

Overall there is a strong relationship between ability in response inhibition and ability in dealing with interference from self perspective, and a weaker relationship between ability in response inhibition and ability in dealing with interference from another's perspective. The implication is that dealing with interference between perspectives requires inhibitory control.

Path from Response Inhibition latent variable to the Relational Error latent variable

For the relational error measured indicator an increased score showed that the participant was not using the information gained from the instructor's perspective. The positive direct path between the response inhibition factor and the relational error factor shows that the ability to successfully inhibit a response is related to the ability to use the information from another's perspective.

To test whether this path masked a path from response inhibition to ambiguous errors, an alternative model with a path from response inhibition to ambiguous errors was tested (without a path from response inhibition to relational errors). The path between the two error variables was from ambiguous to relational. In this model the path between response inhibition and ambiguous errors only approached significance. This suggests that the stronger direct relationship is between response inhibition and relational errors.

The direct path between the two latent variables of the Keysar task could also be replaced by a covariance between their error terms, representing a shared variance that is unexplained by the inhibitory model. Including a direct path means that the relationship shown accounts for some of the variance in the model as a whole. This would also suggest that ability in response inhibition is related, indirectly, with performance in ambiguous trials. This relationship would be mediated by the relational trials. As there is only a direct path to the relational error latent variable from the response inhibition latent variable that is significantly different from zero, the implication is that relationship between response inhibition and ambiguous errors will be mediated by performance in the relational trials. The direction of the path between the two latent variables can also affect the model fit and the path estimates.

There is therefore a direct relationship between response inhibition ability and ability in passing relational trials, and an indirect relationship between response inhibition and ability in passing ambiguous trials. An interpretation is that passing a relational trial requires response inhibition to deal with the competing perspective information (of self and instructor). Participants are presented with two potential referents for a critical instruction, and need to take on the instructor's perspective to select the correct one. There are in essence two separable go signals, as there are two alternative referents (for example, two 'small balls' (see Figure 3.7)), one from their perspective and one from the instructor's perspective. Participants have to respond to one signal and not the other, with the knowledge that the items have different properties (position or size) providing a distinction between the items. Due to the inherent perspective difference cueing due to the ambiguity of the instructions, the ambiguous trials may not require response inhibition directly. The two potential referents have the same name, and so the process that works in the relational trials will not compute for the ambiguous trials as there is no clear distinction between the items in terms of size or position. However, in the current model, performance on the relational trials that do involve response inhibition can predict performance on the ambiguous trials, which does suggest that similar processes are involved if the relationship between the variables is a direct path. In addition, the perspective difference cueing may make the ambiguous trials less effortful, and hence less directly reliant on executive function. The reliability of the ambiguous trials was also lower. This was perhaps due to the lower variance within the task (the range of participant scores was lower than in the relational trials). This then meant that the estimated error variance was higher. An interpretation of this may be that the ambiguous trials are a less pure measure of ToM use than the relational trials, possibly due to the perspective cueing aspect involved. This may mean that more than one executive function is tapped by the processes involved, resulting in there not being a direct relationship between response inhibition and the ambiguous errors latent variable in this model. This is supported by the covariances involving the ambiguous indicator error term.

Another interpretation of this part of the model is that people can differ on their propensity to take on another person's perspective (Wu & Keysar, 2007). This is more likely to be represented by a covariance between the relational and ambiguous latent variables, as it is not explicitly related to inhibition. In this case, the relational trials are a better measure of the participants likelihood to take the instructor's perspective, and if they are likely to do that (and perform well in these trials), then they are also likely to take the instructor's perspective in the ambiguous trials and perform well in those too. If they aren't as likely to take the instructor's perspective, they would tend to perform adequately on the relational trials, but would not be as good on the ambiguous trials due to the relative difficulty in selecting one of the two items. This gives another account for the relationship between relational and ambiguous errors and for the direction from relational to ambiguous, in addition to a purely executive function based account.

Covariances

As noted, there were covariances added from the cued recall (interference) error term and the go / no go (picture) error term to the ambiguous errors error term. This indicates that there is some common variance between these tasks that is not explained by the current model. As this model focuses on inhibitory control, the implication is that the common variance is not inhibitory in nature, and may be another executive function. The developmental literature (esp. Carlson & Moses, 2001; Carlson et al., 2002; Carlson, et al., 2004) shows that inhibitory control and working memory are associated with false belief performance (but that conflict inhibition tasks predicted false belief performance over and above working memory, possibly due to their tapping of both inhibitory control and working memory), so the common unexplained variance may be working memory or a memory construct. For the ambiguous trials, the perspective cueing may result in working memory being needed to hold both perspectives in mind in order to be able to select between them. This may be the basis of an error-correcting strategy, but may also involve some level of response inhibition to deal with any interference between the perspectives. This may account for the potential indirect relationship with response inhibition. The presence of another executive function in the underlying processes of theory of mind is sound theoretically, as it is unlikely that such a complex set of processes as theory of mind would be attributable to only one (inhibitory control) executive function, even if that has two components (response inhibition and response selection).

The amount of variance of the ToM latent variables explained by the model also differed. The variance explained of the visual perspective latent variables was approximately 17%, and of the Keysar latent variables approximately 45%. The implication of this difference is that the processes involved in the Keysar task rely on executive function to more of an extent than those involved in the visual perspective task. However, this is only true of inhibitory control as the executive function. Other executive functions may contribute to the processes involved, but are not included in the current models. It is also possible that the relationship between the Keysar variables explains more of their variance than the relationship between them and response inhibition. This would mean that the executive function requirements of the two tasks are more similar. Overall, although this model is applicable only to the current data set, the two sets of theory of mind tasks, which are both level-one perspective taking tasks, show similar associations with the inhibitory control latent variables, but show no correlation between their task pairs, and have differing amounts of variance explained by the (inhibitory control) model.

This evidence suggests that one possibility is that there could be two different sets of underlying processes for the two ToM tasks. Both require inhibitory control, but one is a relatively fast process, with any processing or interference costs being shown by increases in response time rather than errors. The other may require more inhibitory control and potentially other executive functions, and be a more flexible process as a result. Because of this, this process is more prone to errors (and any costs or interference are shown by errors rather than increases in response time).

Another possibility is that the lack of a relationship between the tasks may be due to task demand differences. As described earlier in the thesis, the visual perspective task requires the participant to observe a sequence of images (a cue as to what perspective to take; the number of circles to verify from that perspective; the image itself) and then to respond by pressing the appropriate mouse button. This involves inferring the alternate perspective, maintaining and using the information from that perspective and dealing with any interference. The Keysar task requires the same processes, but the participant additionally has to follow auditory instructions to select a referent, and then to click and drag the item as per the instruction. This means that they need to integrate the information from the instructor's perspective with their instruction. Therefore even though the two tasks are in essence both level-one perspective taking tasks, as the participant needs to take another's perspective into account in order to successfully complete a trial, some of the individual task demands are different. This could explain the lack of a correlation between the two task pairs of latent variables, rather than there being two different processes that underlie the two different tasks. This could be due to the Keysar task being quantitatively more difficult than the visual perspective task, which could result in the recruitment of different executive functions, or perhaps the recruitment of more of a given executive function (Stuss & Alexander, 2007). However, the demands of the two tasks show more similarities than differences, suggesting that there should be at least some significant correlation between them. The absence of such a correlation would suggest that a two-system explanation is more likely than one based on task demands.

A final possibility is that the common demands of the two tasks account for very little of the variability of either task. As the likelihood is that the common task demands are ToM processes, this would suggest that ToM plays very little role in either task, which seems unlikely. If this was true, it would result in there being no correlation between the two tasks, as the common variability would be low.

In either case, the implication is that the individual differences in ToM will depend on the type of ToM task that is used, and the relative task demands. Ways of clarifying whether task demands or different underlying processes account for the two separable and uncorrelated tasks could include using different tasks to see whether they were also separable on the same basis of the two processes involved. This could be done by the design of a novel level-one perspective task whose difficulty can be increased. The differing task demands explanation would be supported if the version with increased difficulty did not correlate with the original version. Tasks could be designed that are more equal in terms of task demands but that can be categorised as using one system or the other in order to see if they were still uncorrelated. If this was the case, then the two-system explanation would be supported, as task demands would be equal. An issue to consider is how to systematically define the difficulty of the tasks and the respective task demands that are involved. To run another individual differences study would have been difficult due to time constraints, so the technique of dual tasking to look at the contributions of executive function to complex tasks was used. This technique allows the investigation of whether executive function is involved in level-one perspective taking generally. This approach will be detailed in Chapter 8.

7. High and low inhibitory control groups

In order to cross-check the validity of the overall model findings in the individual differences study, the performance of participants in the executive function tasks was compared to their performances on the ToM tasks. If the relationships found in the SEM model are valid, then the high and low performing groups on a given latent variable of executive function (established on the factor scores in the model) should also differ in their performance on the ToM tasks linked to that latent variable in the SEM model.

Therefore it would be predicted from the model that high and low groups on the response inhibition factor would differ in their performances in the visual perspective task (specifically on egocentric interference) and on the Keysar task (specifically in relational errors). High and low groups on the response selection factor should not differ on any of the ToM tasks.

The response inhibition factor is positively related to the ToM factors: if the factor score increases, the ToM factors scores will also increase. As an increase in task DV is indicative of an increase in interference or errors (for inhibition tasks and for ToM tasks), low scores on the inhibitory factors show a high level of inhibitory control, whilst a high score on the factors show a low level of inhibitory control. The low inhibition groups would be expected to show greater interference effects in the visual perspective tasks and a greater number of errors in the Keysar task compared to the high inhibition groups.

Initial analyses

Using the factor score weights calculated in AMOS (the regression weights of the measured indicators for each factor) a score was calculated for each participant on each inhibitory factor[1]. The 20 lowest scoring and 20 highest scoring participants on each factor were then identified and grouped (the

[1] Participants were also grouped using the factor scores from the EF factor model, and by using a single task from each factor as an exemplar of that factor. Results from these alternative analyses showed a similar pattern to the method chosen.

remaining 101 participants on each factor were classed as 'medium' and were not analysed here), forming two independent variables with two levels:

Response Inhibition: high IC group and low IC group

Response Selection: high RS group and low RS group

The groups were created for each factor independently, but of the participants who were classed as a high or low score for a factor, only nine also had a high or low score for the other factor. Of these nine, three had the same classification in both factors (three low on RI and RS), and six had different classifications in the factors (three low on RS and high on RI; three high on RS and low on RI). The remaining 31 participants scored either high or low on one factor and were classed as medium on the other factor.

The performances of the high and low groups from each executive factor on the ToM tasks were analysed using separate ANOVAs for each ToM dependent variable and for each executive factor. The dependent variables were egocentric interference and altercentric interference from the visual perspective task, and relational errors and ambiguous errors from the Keysar task.

F1: Response Selection (IV = high or low RS group)

There was no effect of group on the relational errors ($F_{(1, 38)} = 0.37$, $p = 0.55$, $\eta_p^2 = 0.01$) and ambiguous errors ($F_{(1, 38)} = 0.61$, $p = 0.44$, $\eta_p^2 = 0.02$) from the Keysar task. The high RS group did not perform differently than the low RS group in the Keysar task.

There was no effect of group on egocentric or altercentric interference ($F_{(1, 38)} = 0.88$, $p = 0.35$, $\eta_p^2 = 0.02$ and $F_{(1, 38)} = 0.00$, $p = 0.97$, $\eta_p^2 = 0.00$ respectively), so there was no difference in the performances of the RS groups on the visual perspective task.

F2: Response Inhibition (IV = high or low IC group)

There was a main effect of group on the relational errors from the Keysar task ($F_{(1, 38)} = 9.93$, $p \leq 0.01$, $\eta_p^2 = 0.21$), and on the ambiguous errors ($F_{(1, 38)} = 5.07$, $p = 0.03$, $\eta_p^2 = 0.12$). The high IC group performed significantly better than the low IC group on the relational trials and the ambiguous trials.

There was a main effect of group on egocentric interference ($F_{(1, 38)} = 4.38$, $p = 0.04$, $\eta_p^2 = 0.10$) and altercentric interference ($F_{(1, 38)} = 10.76$, $p \leq 0.01$, $\eta_p^2 = 0.22$). The high IC group had significantly lower interference effects than the low IC group on both self and avatar perspective trials.

The response selection high and low groups did not differ in their performance on both the relational and ambiguous errors from the Keysar task or the egocentric and altercentric interference effects from the visual perspective task. This is consistent with the SEM model, which has no direct paths from the response selection factor to any ToM latent variable.

There was a difference for the response inhibition groups on the relational and ambiguous errors from the Keysar task and for the egocentric and altercentric interference effects from the visual perspective task. This is consistent with the SEM model in there being differences in performance in the Keysar task and in the visual perspective task based on response inhibition ability. This difference in performance was found in the task measures that were directly linked to response inhibition in the final statistically best fitting SEM model (relational errors and egocentric interference) and also with the measures indirectly linked to response inhibition (ambiguous errors and altercentric interference). These findings support model D in Appendix D that has paths from response inhibition to both interference effects, rather than the final model in Chapter 6. The effect size of group is larger for altercentric interference than for egocentric interference, which is the opposite finding from the SEM model (for both the best-fitting statistically and the alternative model D).

Secondary analyses

In order to investigate the different performances of the high and low inhibitory control groups on the ToM tasks, group was used as a factor. These analyses would show whether the high performing group were more efficient in the ToM tasks compared to the low performing group. In the visual perspective task this would be shown by the consistency effects being different for the groups, with a larger consistency effect in the low performance group because of greater difficulty in resolving conflict between the inconsistent perspectives. For the Keysar task, this would be shown by a higher error rate in the low performance group. This would give some indication of whether good executive function ability results in better (faster and less error-prone) ToM performance. Therefore, for the visual perspective task, the analyses were two 2 x 2 mixed ANOVAs on response times and errors separately: Consistency (consistent v inconsistent) and Group (high v low). Perspective was analysed separately, as only the consistency effect was of interest. For the Keysar task, the performance of each RI group on the number of relational and ambiguous errors was analysed by using a one-sample t-test with a theoretical value of zero.

Visual Perspective: Response Inhibition factor only

Self perspective

There was a main effect of consistency, with the inconsistent response times (733.93ms) significantly longer than consistent response times (656.77ms) ($F_{(1, 38)} = 76.27$, $p \leq 0.01$, $\eta_p^2 = 0.67$), and a main effect of group ($F_{(1, 38)} = 17.93$, $p \leq 0.01$, $\eta_p^2 = 0.32$), with the high performance group significantly faster than the low performance group. There was also a significant interaction between consistency and group ($F_{(1, 38)} = 10.76$, $p \leq 0.01$, $\eta_p^2 = 0.221$). This suggests that the groups show differing consistency effects.

The two groups were then analysed separately. The low performance group showed a main effect of consistency ($F_{(1, 19)} = 62.60$, $p \leq 0.01$, $\eta_p^2 = 0.77$), with response times in the inconsistent condition being significantly longer than those in the consistent condition. This was also the case when examining the high performance group only ($F_{(1, 19)}$ = 17.55, $p \leq 0.01$, η_p^2 = 0.48). Both groups showed a consistency effect, indicating that both groups showed a cost in resolving the conflict between the inconsistent perspectives.

Avatar perspective

There was a main effect of consistency with the inconsistent response times (765.06ms) significantly longer than consistent response times (637.36ms) ($F_{(1, 38)}$ = 64.91, $p \leq 0.01$, η_p^2 = 0.63). There was a main effect of group ($F_{(1, 38)}$ = 15.03, $p \leq 0.01$, η_p^2 = 0.28), with the high performance group significantly faster than the low performance group. There was also a marginal significant interaction between consistency and group ($F_{(1, 38)}$ = 4.06, p = 0.05, η_p^2 = 0.10). These results also suggest that the groups showed differing consistency effects.

The two groups were again analysed separately. The low performance group showed a main effect of consistency ($F_{(1, 19)}$ = 35.11, $p \leq 0.01$, η_p^2 = 0.65), with response times in the inconsistent condition significantly longer than those in the consistent condition. This was also the case when examining the high performance group only ($F_{(1, 19)}$ = 32.86, $p \leq 0.01$, η_p^2 = 0.63). Again, both groups showed a consistency effect, indicating that both groups showed a cost in resolving the conflict between the inconsistent perspectives. All of these differences can be seen in Figure 7.1.

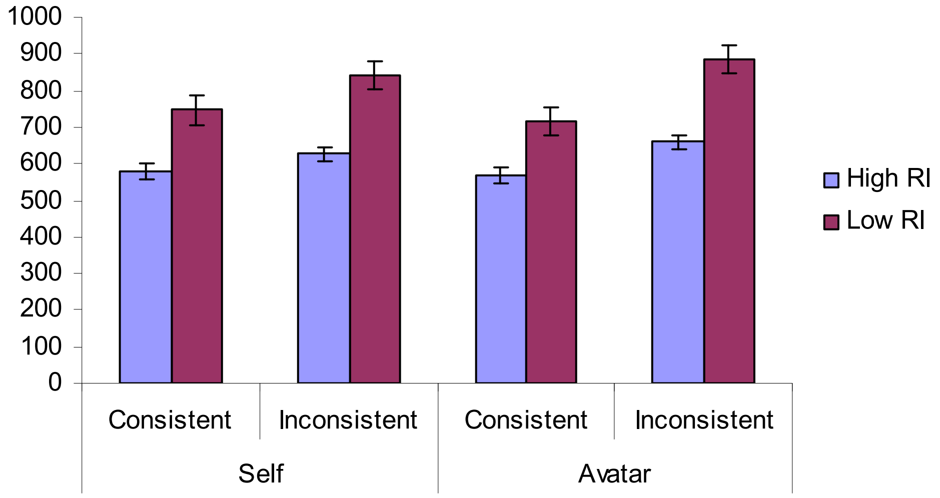

Figure 7.1: Response times (and standard error) by condition and group

For the self perspective trials the identical error analyses resulted in a main effect of consistency ($F_{(1, 38)} = 17.24$, $p \leq 0.01$, $\eta_p^2 = 0.31$). There was no effect of group ($F_{(1, 38)} = 0.01$, $p = 0.94$, $\eta_p^2 = 0.00$) and no interaction between consistency and group ($F_{(1, 38)} = 0.17$, $p = 0.69$, $\eta_p^2 = 0.00$). The avatar perspective trials also showed a main effect of consistency ($F_{(1, 38)} = 40.98$, $p \leq 0.01$, $\eta_p^2 = 0.52$). There was no effect of group ($F_{(1, 38)} = 0.04$, $p = 0.85$, $\eta_p^2 = 0.00$) and no interaction between consistency and group ($F_{(1, 38)} = 1.30$, $p = 0.26$, $\eta_p^2 = 0.03$). Therefore there were no differences between the high and low response inhibition groups in the consistency effects of errors on the visual perspective task.

Overall the response inhibition groups differed in response times to both avatar and self perspective trials, with the high response inhibition group being significantly faster in both. Both groups were also significantly faster in the consistent trials than the inconsistent trials. There was a significantly larger consistency effect in the low response inhibition group than in the high response inhibition group in both the avatar ($F_{(1, 38)} = 4.06$, $p = 0.05$, $\eta_p^2 = 0.10$) and self perspective trials ($F_{(1, 38)} = 10.76$, $p \leq 0.01$, $\eta_p^2 = 0.22$). This suggests that the high inhibition group were more efficient in the ToM tasks than the low inhibition group in terms of speed, as the smaller consistency effect suggests they could resolve the inconsistent perspectives faster. There were no differences in the errors made. This suggests that better executive function can lead to better ToM performance. However, the high performance group still showed performance costs as shown by the consistency effects.

Keysar task:

Relational and Ambiguous errors: Response Inhibition factor

Relational errors

Examining the experimental trials only showed a main effect of group ($F_{(1, 38)} = 11.71$, $p \leq 0.01$, $\eta_p^2 = 0.24$), with the number of errors made by the low response inhibition group being significantly higher than that made by the high response inhibition group. The number of errors made by each group was then compared to zero (using a one-sample t-test with a theoretical value of zero).

The high response inhibition group made significantly more errors than zero (t (19) = 3.20, $p \leq 0.01$), with a mean difference of 1.40. The low response inhibition group also made significantly more errors than zero (t (19) = 6.25, $p \leq 0.01$) with a mean difference of 4.10.

Ambiguous errors

Examining the experimental trials only showed no main effect of group ($F_{(1, 38)} = 11.71$, $p = 0.06$, $\eta_p^2 = 0.09$), with the number of errors made by the low response inhibition group being slightly higher than that made by the high response inhibition group. This would support the lack of direct link between response inhibition and ambiguous errors in the SEM model. The number of errors made by each group was then compared to zero (using a one-sample t-test with a theoretical value of zero). The high response inhibition group made significantly more errors than zero (t (19) = 2.29, $p = 0.03$), with a mean difference of 0.65. The low response inhibition group also made significantly more errors than zero (t (19) = 5.27, $p \leq 0.01$) with a mean difference of 1.40.

Both groups made errors, but the low response inhibition group made significantly more than the high response inhibition group (ToM).). The data suggests that although good inhibitory ability results in better ToM performance, errors will still be made (there is no 'perfect' ToM).

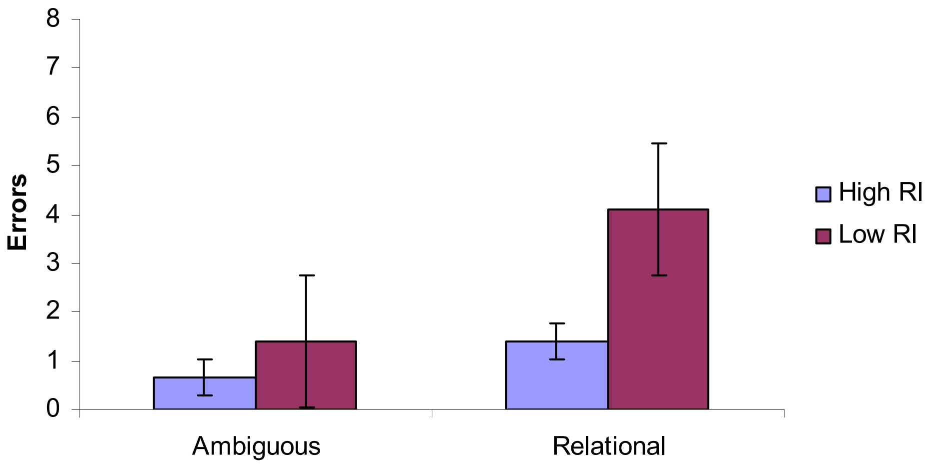

Figure 7.2: Mean number of relational and ambiguous errors (and standard error) by response inhibition group

Summary

The findings show that there is a relationship between response inhibition and performance in both measures of each of the ToM tasks. This is consistent with the findings of the alternative individual differences model (model D from Appendix D). The secondary analyses show that better executive function ability is linked to better, but not perfect, ToM performance. The converse, that lower executive function ability is linked to worse ToM performance, is also shown.

8. Dual-task

Background

The previous chapters hypothesised a link between inhibitory control ability and ToM performance. Using a dual-task design allows the testing of whether or not these hypothesised inhibitory resources used for ToM are actually necessary for efficient ToM performance. Unlike a correlational design (which is similar to that used in the individual differences study) that can only show that an executive component is associated with a target (or primary) task, a dual-task design allows the experimenter to test whether one process (tapped by the secondary task) is necessary for another (required by the primary task). This would be shown by decreased performance in the primary task in the dual condition.

Dual-task studies have focused on working memory contributions (McKinnon & Moscovitch, 2007) and inhibitory control (Bull et al., 2008) to ToM. The tasks used in these studies are standard ToM tasks (the reading the Mind in the Eyes task (Baron-Cohen, Wheelwright, Hill, Raste & Plumb, 2001), and Stories tasks (similar to those in the studies by Happe, 1994; Channon & Crawford, 2000; Stone et al., 1998). The executive function tasks used as secondary tasks included a two-back test (designed to tap working memory; used in McKinnon & Moscovitch, 2007), and an inhibition task, switching task and updating task (Bull et al., 2008), all of which had some effect on the ToM tasks.

More specifically, the ToM (Stories based) task was affected by the two-back test in McKinnon and Moscovitch (2007) (both second-order and first-order task performance was significantly affected, and second-order significantly more than first-order). This would indicate a need for working memory in the Stories ToM task. In Bull et al. (2008) the experimental (ToM) Stories task and the control version were both affected by all the executive tasks and The Eyes task was only affected by the inhibitory secondary task. The evidence therefore suggests some role for working memory in the Stories ToM tasks (McKinnon & Moscovitch, 2007), and for inhibitory control in the Eyes task (Bull et al., 2008). However, the decreased performance of both the ToM Stories task and the control Stories task in Bull et al. (2008) in dual conditions of all the secondary executive tasks suggests that as both versions require the same general executive resources, there is not one that is specifically related to the ToM Stories version. This goes against the relationship found between working memory and ToM (as tapped by the Stories task) by McKinnon and Moscovitch (2007).

However, one issue that needs to be considered are the incidental demands of the primary task. In these cases these were the incidental demands of the ToM tasks. These incidental demands could be disrupted by the secondary task, which would then affect performance of the ToM task, even though the interference is not with the ToM aspect of the task. If the incidental demands of the tasks are above and beyond the actual difficulty of the ToM component of the task, the interference caused by the secondary task would be due to incidental demands and not to ToM.

In summary, inhibition is therefore linked to performance in the Eyes task, and may be used in the inhibition of automatically generated (socially attributed) responses to the facial features in the task. The possibility of inhibition being required to select the most appropriate response from plausible alternatives was ruled out by the lack of interference in the dual condition of the control version of the Eyes task, which has the same response selection element (Bull et al., 2008). The Eyes task associated with inhibition in Bull et al’s (2008) study does not explicitly involve perspective taking, an established component of ToM.

The current study therefore looks at the relationship between inhibitory control and perspective taking in ToM, in the form of two separate level-one perspective taking experiments, the Keysar task and visual perspective task, using a dual-task design.

The relationship that was established by the individual differences study only indicates that inhibitory control and ToM were related, but does not show if inhibitory control was necessary for ToM. The dual-task study could establish whether this was supported or not.

As only one secondary task was used in the study, the most established inhibitory control component of response inhibition was chosen as the resource of that secondary task. This is also the inhibitory construct that was related to both the Keysar task (relational errors) and the visual perspective task (egocentric interference) in the individual differences model. The secondary task that was used to tap inhibitory control was based on the pilot study created by Apperly, Samson, Carroll and Carroll (unpublished). The main demand of the task is to carry out a response that is not the dominant (or learned) response to the stimulus. This therefore involves the inhibition of a dominant response, the definition of response inhibition.

In Apperly et al. (unpublished) several different secondary tasks were piloted for use in a later study. The one chosen used either words (‘one‘ or ’two‘) or beeps (one beep or two beeps) that participants heard and responded to with key presses either incongruently (hear ’one‘ or one beep, respond with two key presses; hear ’two‘ or two beeps, respond with one key press) or congruently (hear ’one‘ or one beep, respond with one key press; hear ’two‘ or two beeps, respond with two key presses). The results suggested that participants’ performance was worse in the incongruent condition. The specific inhibitory component being tapped by the incongruent condition is response inhibition, as the tendency is to respond congruently, and to stop this dominant response, response inhibition is required.

However, the task may also tap response selection as there are two possible responses, one for each stimulus. Therefore the participants may respond based on a priori knowledge of the stimuli rather than by inhibiting a dominant congruent response. It is also possible that the task taps other executive functions, and may have incidental task demands that may affect the primary tasks. These issues are indicative of the general problem of task impurity that occurs when using a single task to tap a single theoretical construct.

Nonetheless, the findings from the individual differences model show that response selection has no relationship with either of the primary ToM tasks, which suggests that even if the secondary task does tap that resource it will not disrupt the primary tasks on that basis. As the secondary task does also require response inhibition (in order to inhibit dominant responses as above) any disruption to the primary tasks is likely to be due to the sharing of that resource.

Performance in the secondary task will be impaired in the dual-task conditions if it shares a common resource with the primary tasks. Based on the individual differences findings, the visual perspective task should disrupt secondary task performance as it shares a demand for response inhibition. Likewise, the Keysar task will also disrupt secondary task performance as it also requires response inhibition. The level of disruption caused in the secondary task performance should be greater for the Keysar task as it has a greater reliance on executive function.

The individual differences findings suggest that dealing with interference between perspectives in the Keysar task requires response inhibition, and hence this should be disrupted by the secondary task in the dual condition. The measure of error rates in this task means that for both Keysar measures (relational errors and ambiguous errors) any interference would be shown as an increase in error rate (as this would be indicative of failing to inhibit self perspective, and moving items that only the participant can see). The two-system approach suggests that performance in the Keysar task is likely to be impaired in the dual-task condition due to its requirement for response inhibition. The task demands explanation would also suggest that the Keysar task may be impaired in the dual-task condition as the same processes that may be affected in the visual perspective task are present.

The individual differences model shows a significant path between response inhibition and relational errors, and a significant path from relational to ambiguous errors. This would suggest that the number of relational errors is likely to increase in the dual condition. The number of ambiguous errors may increase due to the indirect path from response inhibition to them (through relational errors) but not to the extent of the relational errors. The Keysar task may be susceptible to interference due to incidental demands caused by the auditory instructions and any semantic processing involved. The speaker used in the secondary task was chosen for its vibrating cone that allowed participants to feel the vibration of the beeps they needed to respond to. This should reduce the need for the participant to hear the beep, and so reduce the potential auditory interference between those beeps and the instructions of the Keysar task.

The individual differences findings show that in the visual perspective task, response inhibition may be required to resist any interference between the self and avatar perspectives. If this is the case, the result would be a decrease in the performance in the task in the dual condition. As the two measures used in the visual perspective task are interference measures (between consistent and inconsistent conditions), then an increase in the interference between perspectives would be expected. The final individual differences model suggests that disruption to egocentric interference should be greater than to altercentric interference.

Another potential role for inhibition in the visual perspective is in the process of computing the avatar perspective, in addition to the role it has in resolving interference between perspectives. This was not tested in the individual differences model due to difficulty in calculating appropriate measures.

There are different patterns of results that could be expected if inhibition is required to process the avatar's perspective. Response times in the dual condition should increase for the avatar perspective trials in both consistent and inconsistent conditions. The difference in response times between the consistent and inconsistent self perspective trials that is present in the alone condition may also be reduced in the dual condition. Interference to processing the self perspective would become easier to resolve due to the basis of this interference (the avatar perspective) being disrupted by the dual-task. This would be more evident in the inconsistent self condition, so reducing the differences between the consistent and inconsistent self conditions.

If both patterns are shown, then this would go against the two-system approach, as it suggests that inhibition is intrinsically involved in basic visual perspective taking. The two-system approach suggests that response inhibition is required at the level of resolving of conflict between perspectives, not at an intrinsic level of processing perspectives. This pattern of results would therefore favour the task-demands approach.

Method

Participants

Thirty-two students participated in the study for course credits. Participant age varied from 18 to 36, with a mean of 20.9 years of age and a standard deviation of 4.5 years. Written consent was gained from all participants. Five were male, and 27 were female. There were two left-handed participants (one who normally used their right hand) and 31 right-handed participants.

Apparatus

The primary tasks were presented on a 15-inch Samsung SyncMaster 793s monitor connected to a 2.40GHz Pentium-based desktop PC using EPrime 1.1 (Schneider et al., 2002) (Keysar task) or DMDX (Forster & Forster, 2003) (visual perspective task). A standard 102 keyboard was used for responses. The secondary task was presented on a Toshiba Satellite Pro laptop, using EPrime 1.1 (Schneider et al., 2002), using an external speaker to produce the vibrations.

Design

Primary ToM tasks

The main experimental condition was the task condition (with or without the secondary task). The ToM tasks used in this study were nearly identical (in design) to the tasks used in the previous individual differences study. The Keysar task differed in being divided into four separate sections (as opposed to one). This was done in order to vary the section(s) that would be completed under the dual-task conditions. The visual perspective task was already designed in four separate blocks. Each participant completed both primary tasks, half in the alone condition and half in the dual condition. The order of the blocks within the Keysar and visual perspective tasks were identical for all participants but the order of the tasks themselves was counterbalanced, as were the blocks that were under the alone and dual conditions.

The experiment used a within-subjects design. Participants completed all four conditions (visual perspective alone and dual, Keysar alone and dual) in one of four orders:

Table 8.1

Block and Condition Orders for both Primary and Secondary Tasks

	Order			
	A1	A2	B1	B2
	VP 1 & 2	VP 1 & 2	K 1 & 2	K 1 & 2
▼	VP 3 & 4	VP 3 & 4	K 3 & 4	K 3 & 4
	K 1 & 2	K 1 & 2	VP 1 & 2	VP 1 & 2
	K 3 & 4	K 3 & 4	VP 3 & 4	VP 3 & 4

K = Keysar

VP = Visual Perspective

Condition = alone; dual

Secondary Inhibitory control task

The task was based on a pilot study by Apperly, Samson, Carroll and Carroll (unpublished). Participants were presented with a series of trials consisting of either one beep or two beeps. The beeps generated a vibration that could be felt through the palm of the hand. This reduced the interference effects from the shared demands of the auditory processing of the secondary task. They were required to respond incongruently, so that the response to one beep was to tap the spacebar twice, and the response to two beeps was to tap the spacebar once. The trials were in a pseudo-random order with no more than three trials of the same sound in a row. The layout of the task itself varied on the primary task it was paired with, as for both tasks the participants were instructed to stop responding to the beeps once the primary task block had finished. The sequence of trials of the secondary task was designed to be long enough to fill the duration of the appropriate primary task.

Participants did 100 trials of the secondary task on its own to act as a measure of baseline performance. There were two blocks of 150 trials for the visual perspective dual condition, and two blocks of 100 trials for the Keysar dual condition. As participants did all conditions, there was a total 500 experimental secondary task trials in the dual-task conditions.

Procedure

Participants were tested individually. For the secondary task participants were told that they would just see a fixation cross on the screen for the entire experiment and would hear sounds and feel vibrations occurring every two seconds. Participants held the palm of their left hand over a portable speaker positioned before the laptop. They were able to tap the spacebar whilst in this position, and also feel the vibration of the speaker when the beep was presented as part of a trial. They could also clearly hear the same beep. Participants were instructed to press the space bar of the laptop once in response to two beeps, and twice in response to one beep. RTs and errors were recorded.

Participants were given a practice session on the first primary task (for both tasks, the practice session lasted three minutes). They were then given five practice trials on the secondary task, with feedback. After this they were given a further 100 trials on the secondary task alone to act as a measure of their baseline performance. At this point, if participants were to complete the visual perspective task first, they were then given 75 trials of the visual perspective task, or if they were to complete the Keysar task first they were then given 30 instructions of the Keysar task (corresponding to six grids) together with the secondary task in order to practice the dual-task condition. The overall duration of the dual-task condition practice session was the same for both primary tasks.

The four experimental blocks of the first primary task were then completed. Participants were then given a practice session on the second primary task. After this they were given another five secondary task practice trials with feedback, and then another practice session in the dual-task condition with the second primary task of the same duration as the initial dual-task condition practice session. They then completed the four experimental blocks of the second primary task. The order of the primary tasks and the order of the alone and dual conditions were varied as shown in Table 8.1.

Results

Secondary Inhibitory control task

The performance of participants in the secondary task was analysed first. If only primary task performance is taken into account, then it is possible that a finding of no interference in the primary task will be interpreted as meaning the executive component (tapped by the secondary task) is not required for that primary task. However, it is still possible that performance in the secondary task is impaired, which would suggest that there may be a shared resource for the tasks, even though the primary task is unaffected. By taking the performance on both the primary and secondary tasks into account this eventuality is avoided.

Response times

The inhibitory control dual-task was analysed using a 3-way repeated measures ANOVA, with task condition as the factor (baseline, visual perspective task, Keysar task). The response times (for which there were no outliers outside +/- two standard deviations), showed a main effect of task condition ($F_{(2, 60)} = 62.58$, $p \leq 0.01$, $\eta_p^2 = 0.68$). Post-hoc tests indicated that there was a significant difference between the response times to the secondary task in the baseline condition and those in the dual-task conditions (to Keysar: $t\ (30) = 8.81$, $p \leq 0.01$; to visual perspective: $t\ (30) = 9.10$, $p \leq 0.01$). There were no differences between the response times to the secondary task in the two dual-task conditions ($t\ (30) = 1.20$, $p = 0.24$). This can be seen in Figure 8.1.

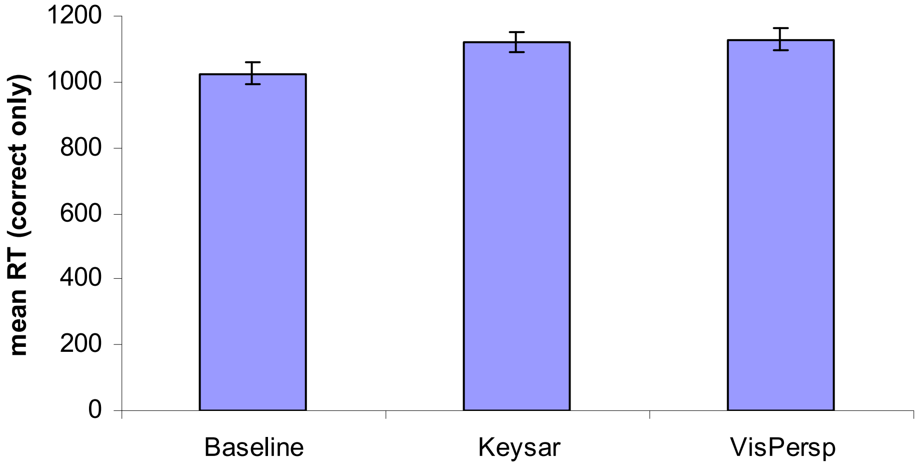

Figure 8.1: Response time (and standard error) by condition in secondary task

Proportion of correct responses

The proportion of correct responses (for which there were three outliers removed at + / - two standard deviations) was also analysed using a 3-way ANOVA, resulting in a similar result, a main effect of task condition ($F_{(2, 54)} = 49.83$, $p \leq 0.01$, $\eta_p^2 = 0.65$). Post-hoc tests showed that there was a significant difference between the proportion of correct responses to the secondary task in the baseline condition and those in the dual-task conditions (to Keysar: t (27) = 8.30, $p \leq 0.01$; to visual perspective: t (27) = 7.49, $p \leq 0.01$). There were no differences between the proportions of correct responses to the secondary task in the two dual-task conditions (t (27) = 0.88, $p = 0.39$). This is shown in Figure 8.2.

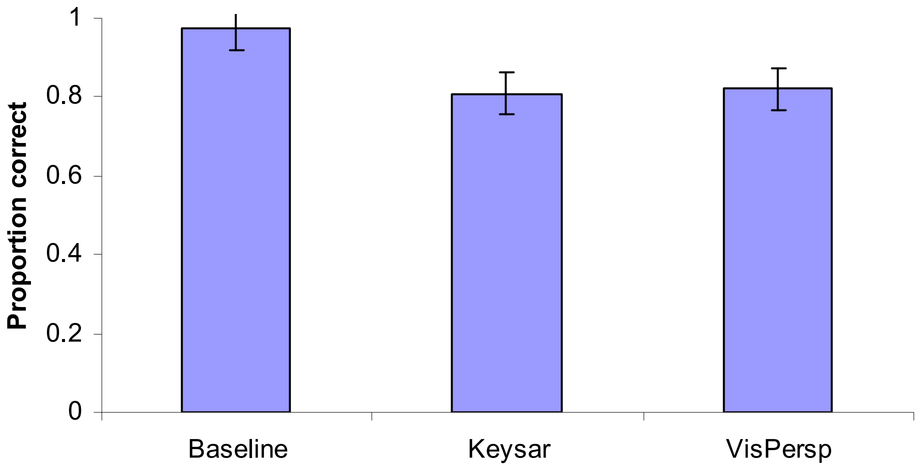

Figure 8.2: Proportion correct (and standard error) by condition in secondary task

The results of the response time and proportion correct analyses show that the secondary tasks performance was disrupted by both primary tasks, and that there was no difference between the disruption caused by the visual perspective task and the Keysar task. This suggests that there may be a common construct or resource in the secondary and primary tasks, as concurrent performance resulted in decreased performance in the secondary task, indicating that the resource needed to process that may have being utilised by the participant to process the primary tasks.

Visual Perspective

The visual perspective task was examined using the same analyses as in the individual differences study, with the addition of the task condition (alone or dual). Therefore the analysis was a 2 x 2 x 2 repeated measures ANOVA (Consistency: consistent v inconsistent; Perspective: self v other; Task condition: alone v dual).

Efficiency scores are shown for brevity of presentation, and were calculated by condition (as response time / proportion of correct responses). The same patterns of results were shown by separate response time and error analyses. Prior to analysis response times 2.5 standard deviations away from the mean were eliminated as outliers, as were response omissions due to the timeout procedure. The results showed that there was a main effect of consistency (efficiency in the inconsistent condition was significantly less than in the consistent condition; $F_{(1, 28)} = 90.39$, $p \leq 0.01$, $\eta_p^2 = 0.76$), whilst there was no effect of perspective ($F_{(1, 28)} = 0.43$, $p = 0.52$, $\eta_p^2 = 0.02$). This is in agreement with the findings from the individual differences study. The additional factor in the analysis was task condition, which had a main effect (efficiency in the dual condition was significantly less than in the alone condition; $F_{(1, 28)} = 115.72$, $p \leq 0.01$, $\eta_p^2 = 0.81$). There was also a significant interaction between consistency and task condition ($F_{(1, 28)} = 13.47$, $p \leq 0.01$, $\eta_p^2 = 0.33$). The interaction between consistency and perspective was the closest to significance ($F_{(1, 28)} = 2.64$, $p = 0.12$, $\eta_p^2 = 0.09$). The remaining interactions were as follows: perspective x task condition: $F_{(1, 28)} = 0.71$, $p = 0.41$, $\eta_p^2 = 0.03$; consistency x perspective x task condition: $F_{(1, 28)} = 0.06$, $p = .81$, $\eta_p^2 = 0.00$.

The interaction between consistency and condition was examined further. In both the alone and dual-task conditions, there was an effect of consistency (efficiency in the inconsistent condition was significantly less than in the consistent condition; alone only: $F_{(1, 28)} = 57.44$, $p \leq 0.01$, $\eta_p^2 = 0.67$; dual only: $F_{(1, 28)} = 59.25$, $p \leq 0.01$, $\eta_p^2 = 0.68$). The differences between the mean inconsistent and mean consistent response times was 132.34ms in the alone condition, but for the dual condition the difference was 268.27ms. The actual difference in response time between the conditions may be caused by the lower efficiency in the dual condition. The interactions and effects can be seen in Figure 8.3.

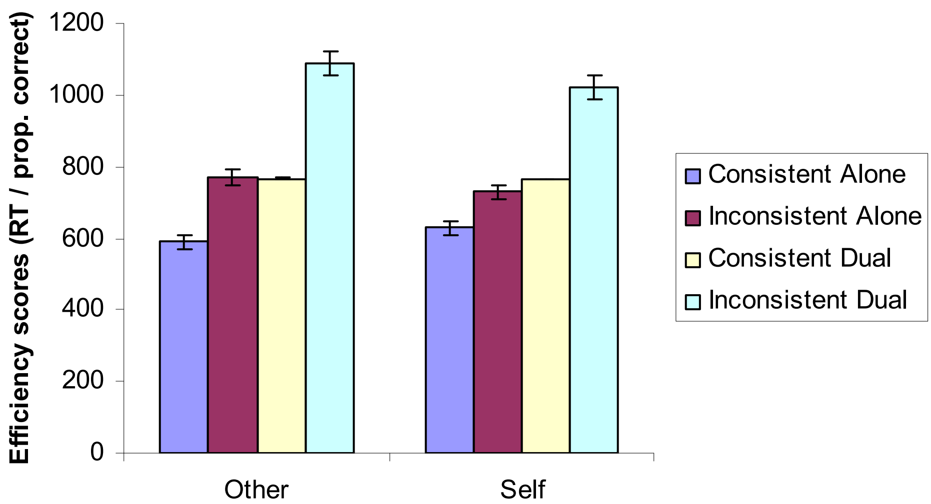

Figure 8.3: Consistency effect (and standard error) by task condition (efficiency scores)

The dual-task condition affects performance in the visual perspective task as well as performance in the secondary inhibitory control task. This fits with the individual differences study's finding of a link between response inhibition and resolving interference.

The consistency effect (the interference effect) of the dual condition (as perspective has been collapsed) is significantly larger than that of the alone condition. Therefore the results show that the secondary task affected the interference between perspectives (the consistency effect) but also that it affected the egocentric and altercentric interference effects equally. This suggests that response inhibition is used in conflict resolution between perspectives. The individual differences model would have predicted a stronger effect of the secondary task on egocentric interference than on altercentric interference. However, the further individual differences models tested and the high and low inhibitory group analyses showed that there was also a relationship between altercentric interference and response inhibition, which supports the current findings.

A secondary interpretation was that if inhibitory control was involved in the processing of the avatar perspective, then the dual-task condition would have shown a reduction in the difference between the inconsistent and consistent conditions of the self perspective. The reasoning is that the resource of inhibitory control needed to process the avatar perspective would be shared with the secondary task. This meant that the processing of the avatar perspective would have been disrupted, making it easier to resolve interference when making judgments about the self perspective. This would have had a greater effect in the inconsistent self condition, so decreasing the difference between that condition and the consistent self condition. As this was not the case, it suggests that inhibitory control is not critically involved in the visual perspective task (at least in taking perspectives), but is more likely to be used in resolving interference between perspectives.

Keysar task

The Keysar task was also examined using the same analyses as in the individual differences study, with the addition of the task condition (alone or dual). The analysis was a 2 x 2 x 2 repeated measures ANOVA (Condition: experimental v control; trial type: relational v ambiguous; task condition: alone v dual).

Errors

Three participants were excluded, as they had previously completed the Keysar task in a different experiment. An additional participant was excluded because of a wrong task selection by the experimenter. T-tests were used as there were no errors made in the control conditions.

A one-sample t-test with a theoretical value of zero showed that participants made significantly more errors than zero in the experimental condition (t (26) = 9.32, $p \leq 0.01$), with a mean difference of 6.37. A paired-sample t-test showed that significantly more errors were made in relational trials than in ambiguous trials (t (26) = 5.32, $p \leq 0.01$), with a mean difference of 2.22. One-sample t-tests with a theoretical value of zero showed that in both experimental conditions participants made significantly more errors than zero (relational: t (26) = 8.18, $p \leq 0.01$, mean difference = 4.30; ambiguous: t (26) = 9.74, $p \leq 0.01$, mean difference = 2.07). This follows the pattern of the individual differences study. There was, however, no difference between the errors made in the alone and dual conditions (t (26) = 1.11, $p = 0.28$, mean difference = 0.52). This is shown in (Figure 8.4).

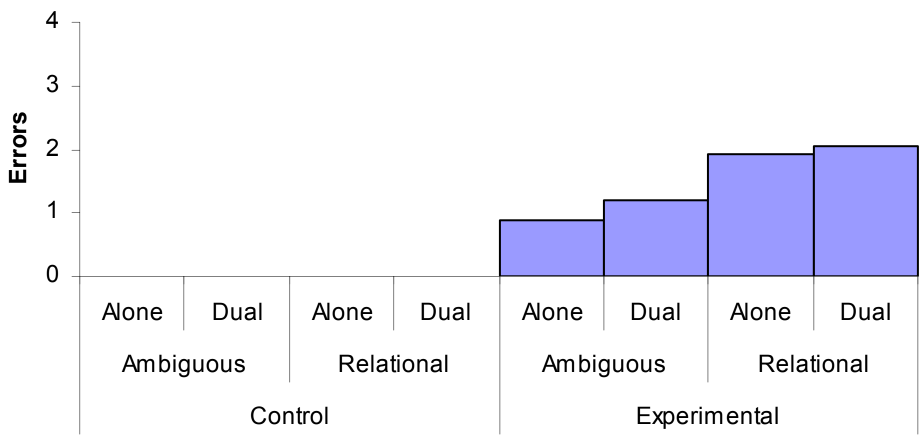

Figure 8.4: Mean number of errors (and standard error) in Keysar task by condition and type

Response times

The same four participants that were excluded from the error analyses were excluded from the response time analyses. 14 further participants were excluded from the analyses. 10 of these were excluded for no response time values, as they responded before the instruction was completed. These were not marked as errors. All of these timeouts were in the experimental condition only. Of these 10 participants, four participants timed out in both alone and dual conditions, two timed out in the alone condition only and four timed out in the dual condition only. The remaining four participants were excluded for response times more than two standard deviations from the mean. Due to the large number of exclusions these response time analyses[1] need to be interpreted with caution but give no reason for doubting the error analyses.

The Keysar task error responses are unaffected by the secondary inhibitory control task in the dual-task condition. This would suggest that the construct that the secondary task is tapping is not necessary for performance in the Keysar task. As this construct is ostensibly inhibitory control, this would contradict the findings from the individual differences study. However, the secondary task is affected by the Keysar task, so it is possible that participants are able to prioritise (consciously or unconsciously) the deployment of their inhibitory resources to the Keysar task rather than the secondary task when necessary. This may also be helped by the nature of the Keysar task (a series of instructions, in which only a few are critical and require processing of perspectives) means that participants are able to follow the control instructions without error, and with no decrement in their secondary task performance. When there is a critical instruction in the Keysar task, they concentrate on processing that instruction, resulting in a decrement in the secondary task performance at that point in time. These periodic decrements in the secondary task performance are shown by the overall decrease in performance in this task in the dual-task condition with the Keysar task (as compared to the baseline). This would also account for there being no decrease in Keysar task performance in the dual-task condition.

The zero response times indicate that some participants (10 of the sample of 29) dealt with the interference from the secondary task faster than other participants, but only in the experimental condition. Four participants did this in the dual-task condition, as opposed to two in the alone condition (four participants responded during the instructions in both conditions). The information needed to

[1] To see whether the pattern of the response times would follow the pattern of the errors (as they did in the individual differences study), the same analysis was conducted on them as for the errors. There was no effect of condition (response times in the experimental condition were the same as for the control condition; $F_{(1, 12)} = 0.02$, $p = 0.88$, $\eta_p^2 = 0.00$). There was a main effect of type, with response times to ambiguous trials being significantly faster than those to relational trials ($F_{(1, 12)} = 36.87$, $p \leq 0.01$, $\eta^2 = 0.75$). There was no main effect of dual-task (alone condition response times were similar to dual condition response times; $F_{(1, 12)} = 2.78$, $p = 0.12$, $\eta_p^2 = 0.19$), and there were no interactions.

select the item (which was the recorded critical measure) is completed in the instruction before the final word(s) that instruct where the item is to be moved. Therefore the participants may have clicked on the item before the last few words and then moved it after the instruction was completed. This would have been recorded as correct and with a zero response time.

Another possibility is shown by the results of the high and low performance group analyses from the individual differences study. These suggest that the association between inhibitory control and ToM task performance can mean that people with high inhibitory control ability can show better ToM task performance. It is possible that those participants who responded before the completion of the instruction in the dual condition have high inhibitory control (as compared to the rest of the sample), meaning that any interference of the secondary task would affect their performance on the Keysar task less than for other participants. The effect of this lesser interference may have manifested in their responding before the instructions were completed in the trials due to increased processing speed.

Discussion

The dual-task results showed that performance in the secondary inhibitory task decreased significantly when in the dual condition. This was true in terms of the number of correct responses and also in the response times to the trials. This indicates that the resource tapped by the secondary task was also used in both of the primary ToM tasks (the visual perspective task and the Keysar task). The decrease in performance of the secondary task was the same for both primary ToM tasks, so in that respect there is no difference in their task demands. This may be indicative of common task demands such as perspective taking, maintenance of perspective and information, and dealing with any perspective interference.

For the visual perspective task, the dual condition resulted in higher response times and higher error rates than in the alone condition. To see whether there was any trade off between response time and error rate, a combined efficiency score was used (response time / proportion of correct answers, which inflates the response time if more errors are made), and the results were similar, with an decrease in efficiency in the dual condition as compared to the alone condition. This is shown by the mean differences between the consistent and inconsistent conditions for the dual (268ms) and alone (132ms) conditions. These results show that inhibitory control may be used in resolving perspectives, but do not say anything about whether it is involved in the process of perspective-taking.

The results also showed that the secondary task affected both egocentric and altercentric interference equally, supporting the findings of the high and low response inhibition group analyses (that there is a relationship between response inhibition and both egocentric and altercentric interference). They also support the choice of the individual differences model with direct paths from response inhibition to both interference effects (Model D from Appendix D rather than the final model of Figure 6.2). The combined findings point to a role for response inhibition in the visual perspective task, probably in dealing with interference between perspectives (as this was the task measure used).

An additional interpretation was that if inhibitory control was involved in the perspective task in the processing of the avatar perspective, the dual condition would result in a smaller difference between the inconsistent and consistent self perspective conditions. This would be due to the processing of the avatar perspective being disrupted, leading to the lessening of that interference with the processing of the self perspective. As this would have more of an effect in the inconsistent condition, the differences between this condition and the consistent condition would be reduced. As the results did not show this pattern of results, it is likely that inhibition is not integral to perspective taking, which goes against the task-demand approach, thereby supporting the two-system approach. Response inhibition may in fact be required for dealing with perspective interference. The requirement for response inhibition may however be at a more unconscious level (Sumner, Nachev, Morris, Peters, Jackson, Kennard & Husain, 2007) than the possibly more actively demanding Keysar task.

Performance in the Keysar task is unaffected by the secondary task in the dual condition. This is true of both error rate and response times, and for both the relational and ambiguous trials. The secondary task performance is affected in the dual condition, so there is some common resource between the two tasks. The immediate interpretation would be that the Keysar task does not rely completely on the resource that is tapped by the secondary (inhibitory control) task as there is no primary task interference, only secondary task interference. However the nature of the Keysar task may mean that the participant is able to consciously or unconsciously prioritise the deployment of their inhibitory resource. On the relatively few critical instructions the participant can focus on the primary task, so performance on the secondary task will decrease for that period. Overall, the results would show a small decrease in secondary task performance and no change in the primary task performance, which is what was observed. The two-system approach would interpret this as meaning that the flexible nature of the system used to pass the Keysar task may allow the tactical deployment of the available resources to the primary or secondary task as needed (whether consciously or unconsciously), which the more inflexible system used in the visual perspective task can not do, resulting in the decreases in efficiency in its dual-task condition.

The findings suggest that there seems to be some common resource to the Keysar, visual perspective and secondary task (due to the impairment in secondary task performance in both primary task dual conditions). This is likely to be response inhibition as this may be required by the common task demands of the ToM tasks. With a two-system view this shared demand is at the level of resolving conflict between perspectives. With a task demands view this shared demand on inhibition is intrinsic to the perspective taking component. Based on the patterns of the results from the three tasks, the role for inhibition seems to be at the level of resolving conflict between perspectives, supporting the two-system approach.

In the current dual-task study, the secondary task was a very simple task that required an incongruent response from the participants. As the dominant response was thought to be congruent, stopping that response in order to respond incongruently should have required response inhibition. The meaning of the dual-task results is constrained by the interpretation of what resource the secondary task used. This is because one of the most important aspects of the dual-task study is the resource measured by the secondary task. The secondary task in a dual-task study measures the (shared) resource of interest, in this case response inhibition. In contrast to the individual differences model, a single task is used to measure that construct. This means that the secondary task must be a reasonable measure of that construct to be valid, whilst in a SEM model several possibly impure tasks are used to estimate a pure latent variable that represents the construct. An individual differences approach means that the theoretical construct being measured is likely to be validly estimated in the model. Dual-tasking relies on the secondary task being a good measure of a theoretical construct (an executive function in the current study), which is less likely to be the case. Nevertheless, in order for this to be an issue in dual-tasking, the other theoretical constructs that the secondary task may measure must be shared by the primary task(s). In this case the individual differences model showed that the other construct, response selection, which the secondary task might tap, did not have a relationship with any of the ToM measures, so obviating this issue.

However, what is lost in possible task validity is gained in the interpretation of the relationship between the primary and secondary tasks. An individual differences SEM model provides evidence that there is a relationship between estimated latent variables, but it can not say whether this relationship is causal or critical. The individual difference model tells us that, in this sample, there is a relationship between response inhibition and ToM task performance, but it does not say whether response inhibition is critical to ToM. Dual-tasking tells us if the resource that tapped by the secondary task is required by the primary task. If this resource is required by the primary task, then performance in the primary task will be impaired in the dual condition compared to alone condition.

In conclusion, the findings can be interpreted as showing that response inhibition is probably needed for fast inflexible perspective taking, and is also used in more complex perspective taking. This is consistent with a more general picture in which executive function has also been shown to contribute to aspects of ToM tapped by questions on complex social interactions (specifically working memory, McKinnon & Moscovitch, 2007) and the Eyes task (inhibition, potentially response selection, Bull et al., 2008).

9. Discussion

The findings on the inhibitory control factors will be discussed first, followed by their relationships with the ToM tasks, and the ToM tasks themselves. The results of the high and low inhibitory control ability groups will then be covered, followed by the dual-task findings. Finally, the implications of these findings and possible avenues of future research will be discussed.

The aim of the thesis was to investigate the cognitive bases of theory of mind performance in adults. The literature showed that executive function had been related to ToM in children and in adults, and that the most widely reported relationship involved inhibition. The next step was to examine the literature and see how inhibition had been treated in terms of its fractionation into reliable sub-components.

Summary of findings

Executive Function factors

The aim of this part of the thesis was to establish reliable and valid latent variables that represented components of inhibitory control, and that could be associated with ToM. The literature varied between three inhibitory components (interference control / cognitive inhibition / behavioural inhibition (cf. response inhibition); Dempster, 1993; Harnishfeger, 1995; Nigg, 2000) and two inhibitory components (response-distracter inhibition / resistance to proactive interference (cf. cognitive inhibition): Friedman & Miyake, 2004).

An initial one factor model was tested which fit the observed data, but only reasonably well. A model with a response and cognitive inhibition factor was also tested, as described in Chapter 2. This had a slightly worse fit to the data than the one factor model. A model with response inhibition and selection factors was also tested as a possible alternative two factor model (see Chapter 5). The fit of this model was significantly different from the actual data, and was worse than both the one factor and two factor (response and cognitive inhibition) models.

The model statistics of the one factor model suggested that the shape-matching task tapped a different theoretical construct to the other tasks. Therefore a model with the shape-matching task loading on a separate latent variable was also tested. The fit of this model was better than all of the previous models. Paths were added that improved the model fit significantly and that were also theoretically justifiable. This resulted in a final model in which response selection was tapped by the Simon, go / no go, go / no go (picture), cued recall, and stop-signal tasks, and response inhibition by the stop-signal and shape-matching tasks. There was also a covariance between the cued recall (control) and the go / no go (picture) measures error terms, indicating a shared unexplained variance.

The tasks themselves almost certainly tapped more than one theoretical construct or executive function, but the task measures were designed to only capture the inhibitory process involved in the task. The Simon and shape-matching tasks both used interference measures, but loaded on different factors. This suggests that the interference was dealt with by different processes in each task: the Simon task interference was dealt with by selecting which stimuli to respond to, whilst the shape-matching task interference was dealt with by the inhibition of the competing distracter stimulus. The go / no go tasks both tapped response selection, as the participants had a priori knowledge of the categorical stimuli and how to respond that resulted in them selecting a response type. However, the go / no go (picture) task required participants to categorise the image stimuli into mammal or bird, and then respond or not based on the initial letter. The task measure was the proportion of responses to no go trials, which mainly relied on response selection, but may have had an element of working memory in the initial categorisation into mammal or bird. As this categorisation was likely to be available before the initial letter (van Turennout et al., 1997), it is possible if categorisation was not complete before the letter processing, interference could result. This suggests that the working memory involved could still affect the final task measure.

The initial cued recall measure was not reliable, and an alternative measure that factored out the variance common to the two component scores (proportion of correct control trials and proportion of correct interference trials) was used. The interference common to both measures was from the distracter task and the different presentation modalities of the two lists; aloud and silent. The remaining variance (in the measure of correct interference trials) that tapped response selection was the interference of the foil word with the target word. Participants were likely to need response selection to choose the word to respond with. The cued recall control measure error term covaried with the go / no go (picture) error term, indicating shared variance. As working memory was suggested to have a role in the go / no go (picture) measure, and is also likely to be required to recall the target word in the cued recall control measure (over the interference of the distracter task and presentation modality), it is likely to be the executive function the two measures have in common.

The stop-signal task tapped both response inhibition and response selection, which is supported by the literature (Rubia et al., 2001). Response inhibition was needed to inhibit the activated response, and response selection may have been involved in selecting how to respond.

The literature suggested that the tasks could have loaded onto three components of inhibition (Dempster, 1993; Harnishfeger, 1995; Nigg, 2000). The fact that the one factor model had a better fit suggests that it is more likely that there is one underlying theoretical construct of inhibition than there being two factors of cognitive and response inhibition (or three factors), which was an unexpected finding. There was also no evidence that a two factor model of response selection (Ikier et al., 2008; Rubia et al., 2001) and response inhibition was any better than either the response and cognitive inhibition model or the one factor model. The data suggest that there are two underlying constructs of inhibition defined here as response selection and response inhibition. The two factor structure is similar to the structure found by Friedman and Miyake (2004).

SEM analyses of Executive Function and ToM

Having established the two inhibitory control latent variables, the relationship between them and ToM was then investigated using a structural equation modelling approach. This approach allowed pure latent variables of the inhibitory components and the ToM measures to be estimated, and for the relationships between these variables to then be investigated. Each ToM latent variable had a single measure (Keysar: relational and ambiguous errors; visual perspective; egocentric and altercentric interference). The relational and ambiguous measures correlated, as did the egocentric and altercentric measures. However, there was no correlation between the measures of the separate tasks (all correlations < 0.09). There are different explanations of this lack of relationship. One explanation is that they are tapping separate systems or components within ToM. Another is that they have different task demands, and hence recruit different executive functions, leading to a lack of a relationship.

In either interpretation, the task demands or processes that are present in the tasks are critical for understanding the cognitive basis of ToM in adults. Both tasks are level-one perspective taking tasks (tasks that require the ability to understand that the content of what one can see can be different from the content of what another sees in the same situation). Demands or processes that are required and are common to both tasks are being able to take another perspective, maintenance of that perspective and the information contained within therein, and being able to deal with any perspective interference (conflict resolution). The Keysar task additionally involves more items (the visual perspective task had a maximum of three discs compared to the Keysar task's four x four grids containing eight items) and also requires participants to integrate the information in the instructor's perspective with the instruction given (in order to select the correct item that is mutually visible). These additional demands may result in an increased requirement of executive function, or the recruitment of different executive functions (Stuss & Alexander, 2007).

Therefore, a conceptual analysis of the two tasks suggests that there might be many processes in common. This would imply that based on the task demands approach, the two tasks should correlate. As they do not, it seems more likely that the two tasks tap different components of ToM. An alternative possibility is that the contribution of these common processes to the tasks variability is so small that there is no overall correlation. As these tasks are ToM tasks, and the common processes are likely to be ToM processes, this is unlikely.

The literature suggests that inhibitory control and working memory have a role in ToM tasks, but the studies tend to involve tasks that are more complex than the current one, which may then mean they recruit more and different executive functions. Some of the ToM tasks used include false belief tasks (both location and content based) and appearance-reality tasks. These tasks have been related to both inhibitory control and working memory (Carlson et al., 2002), and involve the participants knowing the nature of the items presented, and having the language ability to make their response. The current tasks do not require a verbal response, and in the case of the visual perspective task, any specific item knowledge. This is because the participants are shown example grids and the discs are explicitly referred to. Thereafter they simply need to count them. Conceptually it seems likely that inhibitory control would be used in conflict resolution, and perhaps in the role of inhibiting self perspective when taking another perspective. Working memory seems a candidate for the maintenance of perspective and information, as well as for dealing with any increase in complexity of the task (number of items or instructions). The possibility of these resources being required for these processes has been covered by Carlson et al. (2004) and Hughes & Ensor (2005), amongst others. The measures of the visual perspective task are interference effects, which would tap the process of conflict resolution of the two salient perspectives. The measures of the Keysar task are the number of errors made in the ambiguous and relational trials. The errors made may be due to any one or any combination of the processes of the Keysar task (taking another perspective, maintenance of that perspective, and conflict resolution). Overall, the model shows that inhibitory control ability is related to proficiency in conflict resolution (in the visual perspective task) and to more general ToM processing errors (in the Keysar task).

The directions of the paths in the individual differences model between the inhibitory factors and the ToM factors were from inhibitory control to ToM. This was used for two reasons. One was the initial basis for the individual differences study: as executive function is a complex, higher order, set of processes located in a similar area of the brain (frontal lobes) as ToM, which is also a complex higher order process (or set of processes), it was thought that simple components of the fractionation of executive function (for example, inhibitory control, working memory and planning abilities) could also contribute to the processes of ToM. As inhibitory control is a sub-construct of executive function, it would therefore be a sub-construct of ToM. The direction of the direct paths should therefore go from the inhibitory latent variables to the ToM latent variables. The second reason was the relationship found in developmental studies (Hughes & Ensor, 2007), in which early executive function performance predicted later false belief performance. This would also suggest that the direction of the direct paths should be from the inhibitory control latent variables to the ToM latent variables.

The relationships found amongst the inhibitory factors and the ToM measures were between the response inhibition factor and both the egocentric interference and the relational errors in the statistically best fitting model. There was no relationship between the response selection and any of the ToM variables. This is unlikely to be due to the response inhibition tasks having greater variability due to being more difficult, as the more difficult tasks (go / no go (picture) and cued recall) are on the response selection factor. The path estimates of the stop-signal task are also virtually identical for both factors, suggesting that (at least on that task) difficulty is approximately equal. As described in Chapter 6, there were alternate models tested that showed that there was a more theoretically grounded model that was only slightly less well-fitting than the original final model. This model included paths from response inhibition to both egocentric and altercentric interference variables, as well as to the relational errors variable. This model suggests a role for response inhibition in both interference effects, both of which involve conflict resolution. This conceptually and theoretically makes more sense than response inhibition only being required for egocentric interference. The relationship between the interference effects is represented by a covariance in this model that would suggest that there is some unexplained common variance in the interference effects. This could be another, different, executive function or theoretical construct. The covariance may represent working memory, as in order to have conflict resolution between perspectives, it would seem logical that working memory is required to hold those perspectives in mind. This model is supported by the high and low inhibitory control group analyses and the dual-task study.

The relationship between response inhibition and the relational errors of the Keysar task suggests only that response inhibition is required in some or all of the processes involved in the task. The models tested show that a path from relational errors to ambiguous errors provides the best fit to the data. The reason for this path direction may be the relatively low reliability of the ambiguous indicator. Low reliability can equate to low variability, meaning that there is less likelihood of a relationship being shown. The ambiguous trials can not be solved with the process that is used in the relational trials, possibly meaning that performance on them relies on other constructs. The ambiguity of the instruction may also cue the participant to any perspective differences, making it less of a pure measure of perspective taking. In either case, performance in the reliable relational trials (that are more typical perspective-taking trials) is likely to predict performance in the slightly less demanding ambiguous trials. An alternate explanation is that participant propensity to take perspectives may influence performance in the trials (Royzman et al., 2003; Wu & Keysar, 2007), and act as a common underlying process. This propensity would be seen more directly in the relational trials, and if performance in those was high, then the performance in the ambiguous trials, which also require taking perspectives, would also be high.

The covariances between the cued recall (interference) and go / no go (picture) error terms and the ambiguous indicator error term implies a common unexplained variance. As the covariance between the cued recall (control) and go / no go (picture) error terms has been proposed to be working memory, it is likely that this covariance also represents working memory. Ambiguous trials' critical instructions may result in the participants being cued to the perspective difference, suggesting that working memory may be used to hold those perspectives in mind for some form of error-correcting strategy.

Overall these two tasks have similar task demands and also rely on the same executive functions (to different extents, in terms of variance explained). According to a task demand approach, they would be expected to correlate, whereas according to a two-system approach (cf. Feigenson et al., 2004;

Perner et al., 2006; Saxe & Powell, 2006) they would not. The latter approach is supported by the current data.

For a more direct investigation, the task demands could be matched as closely as possible. If the tasks of similar complexity still did not correlate then the two-system approach would be supported, and if they did, then the task demand approach would be supported. A potential way of doing this would be to design a study that systematically varies the complexity of the Keysar task in terms of grid size and so also in the number of items contained in the grid. This should retain the similar requirements for response inhibition whilst varying the differing requirements for working memory, whilst also decreasing the incidental task demands. Participant performance could be analysed at the different levels of complexity – to process the more simple grids, the two-system approach would propose that the process used for the current visual perspective task would be utilised (as children have been able to pass a simpler version of the Keysar task (smaller grids, less items) (Nadig & Sedivy, 2002). The more complex grids would use the process that is used for the current Keysar task. The differences in performance would be borne out in the pattern of processing costs. The cognitively efficient inflexible process shows costs (caused by perspective interference) in increased response time, but not in errors. The cognitively demanding flexible process shows costs (again caused by perspective interference or by not using the information from the instructor's perspective) in increased error rate, but not in any change in response times. A change in the pattern of responses would indicate that there were two separable systems present, and also show exactly where the crossover point was from the use of one system to another. If there was no change in response patterns, then the task demands approach would be supported.

High and Low inhibitory control ability group analyses

These analyses were designed to test whether the relationships found in the SEM model between inhibitory control and the ToM latent variables were supported by analyses that compared the performance on the ToM tasks in high and low executive function ability groups. The high and low performers on each inhibitory factor were calculated and placed into two groups. The performance of these groups on the ToM tasks was then analysed. The results of the initial high and low ability inhibitory group analyses supported the model with direct paths from response inhibition to both interference effects. This was because there was a group difference in both interference effects, whereas the statistically best fitting model would predict a difference only in egocentric interference. The findings were also consistent with the Keysar latent variable relationships, with a direct relationship between response inhibition and relational errors, and an indirect relationship between response inhibition and ambiguous errors. This path, as discussed earlier, may also represent another process or theoretical construct such as the propensity of participants to take an alternate perspective. This may be in addition to the response inhibition element or instead of it. When participants were grouped according to performances on the response selection latent variable, there were no differences on any ToM task performance. This is also consistent with the individual differences model.

In addition to testing whether differences in executive performance led to differences in ToM performance, it was also checked whether the qualitative pattern of ToM performance was the same for the high and low inhibitory control groups. The general findings were that the high performers (on the response inhibition factor) tended to be lower in terms of error rates (Keysar task) and had smaller consistency effects (visual perspective task). The low performers had significantly worse performances than the high performers in all the tasks. The high performance groups still made errors and showed consistency effects (significantly more than zero, but significantly less than the low performance groups): there were no expert ToM performers.

The position of the high and low performance groups on the distribution of the inhibitory factor scores and on the ToM scores were examined to see if any of them lay on an extreme tail of a skewed distribution. If they did the implication could be that the low performance group could be the start of another distribution that could lead to the association of impaired or lower executive function performance with impaired or low ToM abilities (impaired executive function ability has been linked to later impaired ToM in young children with autism; Pellicano, 2007). The distributions for the inhibitory control factor scores were distributed normally, and the high and low performance groups were in the tails of the distributions, as would be expected. The high and low performance groups fell in the main cluster of scores in the distribution of the ToM tasks (which were not normally distributed). This all means that both group types are part of one sample rather than potentially being part of another sample.

Dual-task analyses

The dual task analyses were conducted to see if inhibitory control (specifically response inhibition) was necessary for the two ToM tasks. This was because the SEM models are limited to showing that there is a relationship, not that inhibition is required for ToM. The dual task results suggest that there was a common resource to the secondary task, visual perspective task and the Keysar task, as performance in the secondary task was impaired to the same extent in both of the primary tasks' dual conditions. When compared to the individual differences model and the high and low group analyses, the likelihood is that this common resource is response inhibition. This supports the findings of Bull et al. (2008) that inhibitory control is linked to ToM (in that study measured by the Reading the Mind in the Eyes task). A task demand approach suggests that tasks that are quantitatively similar in terms of difficulty (task demands and processes) are likely to require qualitatively similar executive resources, and hence are likely to correlate. The likelihood that the ToM tasks share the same resource of response inhibition, taken with the majority of task demands being identical, would, according to the task demand explanation, lead to expectation that the tasks correlate. The fact they do not suggests that despite their common resource of response inhibition and shared task demands, they are measuring separate components or systems.

The visual perspective task performance was also impaired in the dual condition. This impairment in performance was similar for both interference effects, suggesting that response inhibition is used for the conflict resolution of perspectives, whether that interference is from self perspective or another perspective. The dual task did not disrupt the process of taking the avatar's perspective, only the process of resolving perspectives in order to make a response based on one and not the other. These results support the choice of the individual differences model with direct paths from response inhibition to both interference effects. Keysar task performance was not impaired in the dual condition. Considering that the amount of variance in the Keysar task that was explained by the inhibitory individual differences model was almost twice as much as in the visual perspective task, this is surprising. The likelihood is that response inhibition is used in the task, but as there are infrequent critical trials the overall results do not show any impairment in performance in the dual condition.

The executive function associated with the visual perspective task is response inhibition (directly for both egocentric interference and altercentric interference). The executive function associated with the Keysar task is also response inhibition. The final model is Model D in Appendix D, replicated below in Figure 9.1.

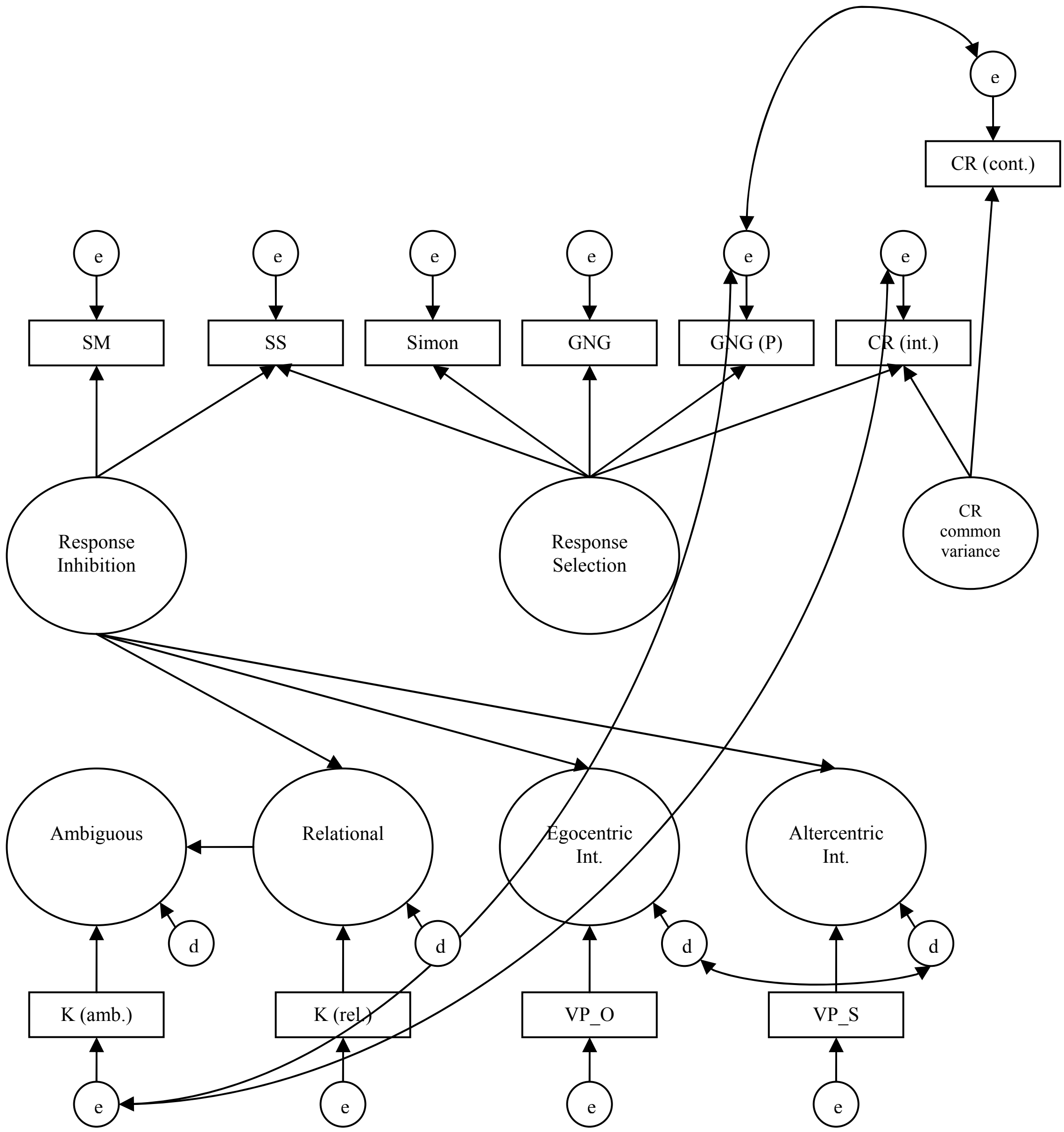

Figure 9.1: Final model

Implications

The combined findings show that executive function ability, specifically response inhibition, is associated with ToM performance in this sample, supporting earlier findings (Channon & Crawford, 2000; Happé et al., 2001; Stone et al., 1998). This suggests that executive function is required for ToM in adults. Executive function has been associated with the development of ToM in children (Carlson & Moses, 2001; Carlson et al., 2002; Carlson, et al., 2004; Hughes & Ensor, 2005; Hughes & Ensor, 2007), and the continued association between these constructs in adults suggests that executive function (in particular inhibitory control) is necessary not only for the development of ToM, but is also an integral part of the fully developed ToM in adults. There is also another potential executive function associated with the ToM performance in the sample, which from the nature of the tasks involved seems likely to be working memory. Working memory has also been linked to ToM in children (Carlson et al., 2002), and these analyses point towards it being also used in ToM in adults.

Response inhibition seems to be involved in dealing with perspective interference (conflict resolution), as shown by the relationship between it and the two visual perspective interference effect measures. The role of response inhibition in the Keysar task is less clear. The errors on this task could have come from several different processes that were involved in the task (conflict resolution, taking of a perspective, maintenance of that perspective), so it is unclear exactly which of these processes required response inhibition. However, as conflict resolution between perspectives is also likely to be needed for the Keysar task, it is possible that this is what response inhibition is required for. Previous literature has suggested that response inhibition is needed for the inhibition of the self perspective (Samson et al., 2005), although there is evidence for it also being needed for the inhibition of any alternate perspective (Samson et al., submitted). These findings show that it is likely to be additionally required for resolving any conflict between perspectives. Conceptually, working memory may be required for the maintenance of the perspective and the information contained therein that is necessary for both tasks. This is represented by the covariance between the interference factors of the visual perspective tasks, and the covariances between the ambiguous factor and the go / no go (picture) and cued recall measures. The level of working memory required is likely to be more for the

Keysar task as there are more items to maintain, and this is shown by the different representations of the working memory aspects of the two tasks.

There is clear evidence from the current study that executive function is involved in ToM in adults. This would seem to be typified by the Keysar task, and is supported by the findings of the individual differences model. This is consistent with existing literature from adult studies (Bull et al., 2008; German & Hehman, 2006; McKinnon & Moscovitch, 2007) and patient studies (Channon & Crawford, 2001; Happé et al., 2001; Samson et al., 2005). Therefore, it seems reasonable to think of ToM as cognitively demanding.

However, there is also evidence from the current set of studies, especially from the dual-task studies, that runs the other way. The dual-task showed that the Keysar task was not disrupted in the dual condition, which goes against the prediction from the individual differences model. This may be because the intermittent critical trials allow participants to stop performing on the secondary task to focus on the Keysar task, which suggests that executive function is required for the task. The results for the visual perspective task in the dual task study showed that inhibition did affect task performance. However, the pattern of results showed that this disruption was caused in resolving interference between perspectives, but not in processing the avatar’s perspective. Therefore computing the avatar’s perspective may have been cognitively efficient. This suggests that there may be two aspects of ToM, one that is cognitively demanding and one that is cognitively efficient.

This two-system explanation could account for the findings that infants and primates can pass perspective taking tasks (Onisihi & Baillargeon, 2005 and Sodian et al., 2007; Tomasello et al., 2003, respectively). The flexible and cognitively demanding process (that is therefore more prone to errors), that is proposed to be used in the Keysar task, may be ToM as it is classically defined. Both processes (or systems) are present in adults, as evidenced by the individual differences model. It would seem likely that executive function allows the flexible process to develop, which would account for the relationship between executive function performance and later false belief performance in children (Carlson & Moses, 2001; Carlson et al., 2002; Carlson, et al., 2004). As primates have limited executive resources (as do infants) they may rely on the inflexible cognitively efficient process and are unable to develop the flexible and cognitively demanding process that we generally term ToM. As both the inflexible and flexible processes appear to be present in adults, it is unlikely that the inflexible process is just a precursor to the flexible process: the flexible process is not just the inflexible process with executive function tagged on for increased processing power. That explanation would fit with a task demand-based explanation, though if this was the case there would be expected to be some correlation between the processes.

The potential separation of these two systems could account for the findings in primates (Tomasello et al., 2003), without having to appeal to the idea of primates having a ToM as it has been commonly defined. This separation would also give a parsimonious account of how infants are able to pass perspective taking tasks at an age when they are unable to pass (the normal) false belief tasks. One issue that has not been resolved is the level of sophistication associated with the inflexible system. Interpretations of the abilities of infants and primates in being able to pass tasks that require perspective taking have often suggested that the participants are able to understand intentions and, to some extent, that the actors in the task have different beliefs to their own (which could be said to be an understanding of false belief). Whilst this interpretation is possible, the line of reasoning it suggests makes it difficult to argue against task designs and demands being the only reasons why primates and infants fail standard false belief tasks. It may be that any additional task demands mean that different executive functions are needed, perhaps to a greater extent. Limited executive resources may be why primates and infants are unable to pass those tasks, and a task demand based explanation can therefore also account for the findings that infants and primates can pass perspective taking tasks but not false belief tasks, as the false belief tasks may have additional task demands that require additional executive resources.

In terms of understanding emotions (of people's faces), it has been suggested that infants (and perhaps primates) are able to understand simple emotions (anger, happiness) at an earlier age than more complex emotions (confusion, apprehension) (Camras, Oster, Campos & Bakeman, 2003; Soken & Pick, 1999). A similar interpretation could be used for the level of understanding of beliefs and intentions associated with the inflexible system of ToM, in that it is possible that infants, and possibly primates, are able to understand simple beliefs (such as knowledge of object location) and intentions (actor wants certain object), but may not understand more complex beliefs or intentions. They may not know why the actor in the task wants that certain object, or understand the explicitly false nature of an actor's belief – they may interpret as being different from their own, but not consciously as being 'false'. However, these are all potential interpretations of the level of understanding shown by infants and primates in perspective taking tasks.

The challenge is to design tasks that have lower task demands and that still require explicit false belief reasoning, and then see if infants or animals (as certain species of bird, such as scrub-jays, have shown evidence of ToM-like abilities; Dally, Emery & Clayton, 2006) are able to pass them. If they are able to pass them, then their difficulty is not with the understanding of false belief, but with the additional, more incidental task demands, supporting the task demand approach. Therefore both potential explanations of the current findings can be related to these findings. However, the fact that there is no correlation between the two tasks implies that it is more likely that there are two systems that can be recruited by adults, and that the faster, potentially more inflexible one is available to infants and primates, as it can be used with limited executive resources.

Limitations

The studies have potential limitations, covered in this section, in terms of the ideal statistical parameters for the analyses, the causation of effect, and also the strength of any interpretation of the analyses. Statistically the sample size of the individual differences study was sufficient not to give any false negative or non-existent associations between both the measured indicators and the latent variables, or between the latent variables themselves. However, some of the actual parameter coefficients for the inhibitory control tasks, although significantly different from zero, are lower than what is normally considered satisfactory in SEM. This may be due to the amount of variance in the indicators attributable to inhibitory control being relatively small. Following this, the remaining variance in these tasks could be accounted for by other executive functions or perhaps is more automatic in nature, and in either case is not explained by the current executive function based model. The reliability estimates of these tasks that could have contributed to the low parameter estimates were however satisfactory in all cases. Therefore, as the parameter coefficients to and the variances of the inhibitory control latent variables are significantly different from zero, the general factor structure shown should be replicable.

However different inhibitory tasks in additional individual difference SEM models should be tested to see whether this is the case. This would also aid in clarifying the definitions of the inhibitory constructs found, and would also allow another potential limitation of the study to be addressed. Ideally the number of tasks used to measure a latent variable is a minimum of three. When this study was designed the number of measured indicators for the proposed latent variables was three each. The factor structure identified showed that this was not the case, and the response inhibition latent variable has only two measured indicators. When this is the case, the parameter estimate needs to be constrained to a specific value (here calculated from its reliability estimate), which is not ideal. Another aspect of the current structure is that the stop-signal task loads on both inhibitory factors. This is again not an ideal situation, as tasks should be designed to primarily tap only one theoretical construct, though in this case literature has suggested that the stop-signal task does tap both of the inhibitory factors defined in this model. Using different and more numerous executive tasks would allow the number of tasks acting as measured indicators for the factors proposed to be three or more, thereby making the factors both more reliable and valid. It would also mean the factor structure found in the current study could be tested to see if it held for different inhibitory tasks.

Some of the issues are also present in the ToM latent variables and their measured indicators. The initial model had all four measured indicators tapping the same latent variable, indicative of a unitary ToM, which would then have a sufficient number of indicators, as per the literature. The correlations suggested that there was no relationship between the ToM tasks, and so there was a possibility of having two ToM latent variables with two indicators each. The levels of the correlations between the two measured indicators of each ToM task indicated that there were potentially four separate, though correlated, ToM latent variables in the model. Single indicator target latent variables are common in SEM studies, as they are used as exemplars of complex processes that are require qualitatively and perhaps quantitatively different simple processes. This is similar to the present model of complex ToM requiring simple inhibitory processes, though this point will be returned to later.

The reliability was not ideal for ambiguous errors or for altercentric interference. This may have led to the lack of a relationship between these latent variables and response inhibition in the statistically best-fitting model. Using more and different ToM tasks would allow the factor structure shown in this model to be replicated (or not), and may also allow more than one indicator to be used to measure any ToM latent variables found.

The direction of causation between inhibition and theory of mind has been said to be from inhibition to ToM (Hughes & Ensor, 2007), but also from ToM to inhibition (Perner, Lang & Kloo, 2002). The current model suggests that the relationship is from inhibition to ToM, as these model statistics are better than for a model with paths from ToM to inhibition. Conceptually inhibition seems less complex than ToM, and so it would seem more likely to contribute to ToM than for ToM to contribute to it.

Some general issues in the interpretation of these results hinge on the type and number of tasks used. As suggested later, different quantitative and qualitative tasks could be used in a similar individual differences study to examine whether the current findings hold. The tasks used in the current study are not classic ToM tasks (like, for example, false belief tasks). The processes involved may not be core processes of ToM (although the dual-task results suggest that the visual perspective task involves some level of cognitively efficient, possibly automatic, perspective taking, which may be), but are involved in the expression of those ToM abilities. Without an ability to resolve conflict between competing perspectives, being able to take those perspectives could be nearly an irrelevance. Likewise being able to use the information gained from taking a perspective allows the ability to understand another's belief or mental state to be used in social situations. However, more tasks need to be used to reach a definite conclusion on the nature of the potential components of ToM.

Future research

The relationships found in the individual differences study between executive function and ToM performance are for this particular sample and these particular tasks. However, these relationships would be expected to generalise. The relationship still needs to be investigated for different executive functions and for different ToM target tasks. One way of doing this would be to use different executive function tasks in the battery to see whether the relationship between inhibitory control and the two target ToM tasks will hold with other (inhibitory control) executive function tasks. Tasks that tap other executive functions that may be present in ToM, such as working memory (which is potentially the explanation of the shared unexplained variance in the current model) could also be added to the executive function battery. The current findings would suggest that the requirements for response inhibition should be relatively similar for both tasks, but that any working memory requirement should be greater for the Keysar task due to the greater number of items to be maintained. This model may be able to show whether the Keysar task requires significantly more working memory than the visual perspective task, as this may lead to the lack of correlation between the tasks. If similar executive function demands are shown for the two ToM tasks when this different executive function battery is used, then the task demands of the two tasks are again likely to be the same. If the ToM tasks then still do not correlate then the two-system approach will be supported. If the task demands are different, then any lack of correlation between the tasks may be due to the different task demands. This approach may also give supporting evidence for the inhibitory control classifications of the current model, and using more tasks is also more theoretically sound for SEM analyses.

Another way of further establishing the relationship between executive function and ToM would be to use different target ToM tasks. ToM tasks such as standard false belief tasks, the strange stories task, and the mind in the eyes task could be included in the model. Using these tasks with the ToM tasks from this study would also mean that more than one measured indicator could be used for any potential ToM latent variables, which is more theoretically sound. If these additional ToM task measures loaded onto the same two separate latent variables that are currently tapped by the Keysar and visual perspective tasks, which then did not correlate, then the two-system approach would be supported. If they all loaded onto one latent variable, or onto latent variables that did correlate, then a more unitary concept of ToM would be supported. It is possible that this model may result in more than two latent variables that represent different aspects of ToM.

Another way of investigating the two-systems versus the task demand approaches would be to vary the complexity of the Keysar task and the visual perspective task to see if there is a change in the pattern of responses at any given point of complexity that would indicate a change in the process or system being used to process the trials. Varying the complexity allows the task demands to also be varied. Using eye-tracking software and hardware the implicit movements of the participant (indicative perhaps of the more inflexible, cognitively more efficient and hence implicit process) could also be compared and contrasted to their explicit movements (perhaps suggestive of the more flexible, more cognitively demanding and maybe more conscious process) through the analysis of both eye movement (implicit) and movement of the mouse (explicit), to give a more detailed and fine-grained set of measures to go with the pattern of actual responses and response times.

A more general idea of future research would be to look into comparing more qualitative measures of ToM with the quantitative measures present in the current study. Quantitative measures of ToM may be reliable, but may not be representative of how ToM is used in everyday social situations. This issue would be addressed by the use of qualitative measures that show more validity. A potential measure is the number of mentalising words (such as ‘think’ or ‘want’) that a person may use in describing their friends (de Wit & Fernyhough, 2006). The higher the number, the better that person may be at mentalising, and hence at ToM. Generally this measure should correlate significantly with a quantitative ToM measure if they tap the same construct. It may however be that a qualitative measure is inherently more complex than a more narrowly defined quantitative measure, resulting in it loading on more than one (ToM) latent variable. Alternatively, it may load on the more flexible ToM latent variable as it requires additional resources such as executive function and language. This could be investigated by using language measures in addition to executive function measures in investigating their relationship to the qualitative and quantitative measures of ToM. The high and low inhibitory control group analyses showed that the level of performance of the high ability groups in the ToM tasks was similar to the overall sample, whilst the low ability groups were significantly worse than the overall sample. The distribution of the scores suggested that the high and low ability groups were in the tails of the normally distributed inhibitory control factor scores, so did not represent other potential samples (of adults who show impaired executive function abilities and hence impaired ToM). This pattern of results suggests that good executive function ability can result in better ToM performance in quantitative measures of ToM. This relationship could again be investigated with qualitative measures to see if executive function is also related to ToM as measured by more valid measures that are likely to be nearer to how ToM is used in common social situations. These two contrasting approaches could therefore provide convergent (if the ostensibly more complex qualitative measures loaded on the more flexible ToM latent variable) or potentially divergent (it loads on the more inflexible latent variable, or on both) evidence for the two-system approach and for ToM in general. It could also inform what resources a qualitative measure relies on (executive functions and / or language ability).

Conclusion

The individual differences model has provided support for the critical role of executive function in ToM in adults. The dual-task study results also supported this relationship. The presence of a relationship between executive function and fully developed ToM in adults suggests that the relationship between them in the development of ToM is critical, and that this relationship is integral to ToM throughout the lifespan.

The battery of inhibitory control tasks loaded on to two separate latent variables, defined as response selection and response inhibition. This categorisation supports the view that the processes that have been defined as cognitive inhibition are not quantifiably different from those that have been defined as response inhibition, and that this definition of cognitive inhibition has been over-extended (Verbruggen et al., 2005). This suggests that the mechanisms involved in response inhibition are the same, or very similar, to those involved in what has been termed cognitive inhibition. This implies that dealing with distracters or irrelevant information once they have entered working memory (cognitive inhibition as defined by Nigg (2000) and Harnishfeger (1995) employs the same mechanisms as response inhibition, in the inhibition of that distracter or that information. However, the fact that there are two components of inhibition does support the general view that executive function can be fractionated into simpler components, but that the existing definitions of the inhibitory control components are not fully supported by the current findings.

The set of studies has also provided evidence for there being two separable systems of ToM (or two distinct processes within ToM). This is evidenced by the lack of correlation between the two target ToM tasks used (which were both level-one perspective taking tasks), even though the relationships of the ToM latent variables to the inhibitory control factors were relatively similar, with the Keysar task having one direct path and the visual perspective task having two direct paths from the response inhibition latent variable respectively. The amount of variance of the ToM latent variables explained by the inhibitory model also differed. The difference in variance explained suggest that the difference between the processes required to pass these two tasks is at least partly due to their differing reliance on executive function, and inhibitory control in particular. The interpretation is that the process used in the visual perspective task is a more cognitively efficient process that is fast, but may be relatively inflexible. The dual-task study results provided evidence that the difference between the two ToM tasks is unlikely to be simply due to task difficulty. The process used in the Keysar task is a cognitively demanding process that is slower but is flexible, but is more prone to errors (due to its reliance on executive function).

These two processes or systems are present in adults, and may be used for different social situations: the cognitively efficient process may be used when relatively simple perspective taking is needed, or fast decisions need to be made on that basis. The fact that they are both present in adults means that the cognitively demanding system is unlikely to be just the cognitively efficient system with the additional processing flexibility of executive function. The cognitively demanding and flexible process may be used in situations where several different beliefs or mental states need to be processes and taken into account in order to guide one's own behaviour or predict someone else's behaviour. In addition, the cognitively efficient process may be the process that allows infants and some animals to pass tasks that require simple perspective taking at an age when they are unable to pass standard ToM tasks (as this process does not rely on executive functions that have either not developed (in infants) or are limited compared to humans (in animals)). This gives a plausible explanation for these abilities, without having to claim that infants and animals are exhibiting evidence of what is the current, singular, definition of ToM. It is also a more parsimonious explanation of this behaviour than potential explanations based on behavioural rules (for example, the infant selectively looks at the last place the object was or where the actor last looked). The cognitively demanding and flexible process is likely to be the process that is currently interpreted as being the ToM that develops from around the age of four (it requires executive function as does the established idea of ToM).

However, this two-system approach needs more evidence to support it. More work is needed, both on the details of the different ToM processes and on the validity of these processes as measures of individual variability in ToM.

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Appendix A

Cued Recall

Table A.1

Cued Recall Words (Blue = Foils; Red = Targets)

	List One (aloud)				List Two (silent)				Cue
Section 1	1	2	3	4	1	2	3	4	
Filler	Cement	Nylon	**Poodle**	Rake					Dog
Interference	Astronomy	**Toaster**	Alto	Conjunction	Ore	**Can Opener**	Syringe	Private	Kitchen appliance
Control	Pitta	Office	Nails	Lantern	Lollipop	Knife	**Flute**	Argon	Musical instrument
Interference	Dinosaur	Polka	**Boots**	Graduate	Tangerine	Great Dane	**Clogs**	Snare	Footwear
Control	Plastic	Mastodon	Cheek	Swine	Seat Belt	Extinguisher	**Typhoon**	Moccasins	Windstorm
Control	Black	Brooch	Mile	Vodka	Lamp	Iron	**Cobra**	Ham	Snake
Interference	Peas	Mirror	**Hawk**	Bourbon	Clamp	Captain	**Osprey**	Quarter	Bird of prey
Filler	Lemon	Eye Shadow	**Waltz**	Mango					Dance
Control	Pineapple	Shears	Rhombus	Tyranny	Article	Asparagus	**Polyester**	Fez	Cloth
Interference	Tympani	Azalea	**Steel**	Stetson	Dishwasher	Zeus	**Nickel**	Betel	Metal
Control	Clause	Onion	Dance	Low Rider	Tea	**Hexagon**	Whisky	Exponent	Shape
Interference	Tuba	Mascara	**Diamond**	Thermos	Mint	Sourdough	**Opal**	Fox Trot	Gemstone
Control	Muskrat	Attic	Duke	Botany	Schooner	Tenor	**Forceps**	Spatula	Surgical instrument
Section 2									
Control	Buttermilk	Hustle	Chihuahua	Bass	Joy	**Sombrero**	Gunpowder	Chin	Hat
Filler	Pronoun	**Brunette**	Watch	Oven					Hair colour
Interference	Cocaine	**Fork**	Peers	Leopard	Torso	**Chopsticks**	Neurologist	Locomotive	Eating utensil
Filler	Maroon	**Skyscraper**	Penny	Hull					Building
Interference	Kitchen	**Mountain**	Panda	Blonde	Rayon	**Sinkhole**	Lips	Celery	Natural Earth formation
Interference	Satisfaction	**Gun**	Hoe	Skating	Noon	**Axe**	Vanilla	Cashew	Weapon
Control	Motorcycle	Crane	Bassoon	Beech	Delete	**Foot**	Physics	Razor	Unit of length
Interference	Tennis	**Bathtub**	Month	Marjoram	Albatross	**Faucet**	Oboe	Season	Bathroom fixture
Filler	Saw	**Oxygen**	Vulture	Talking					Chemical element
Control	Optometrist	Tin	Chief	Reef	Peyote	**Trowel**	Sapphire	Architect	Gardening tool

Interference	Sperm Whale	**Backpack**	Jeep	Loafer	Democracy	**Rope**	Blender	Ghost	Camping equipment
Control	Duck	Shovel	Nut	Hydrant	Socks	**Basil**	Canteloupe	Marxism	Herb
Section 3									
Control	Cheese	Belly Dancing	Pointer	Tom Tom	Plate	Shock	**Encyclopaedia**	Glucose	Reference book
Filler	Yard	Ant	**Cinnamon**	Mahogany					Spice
Interference	Lumber	Garlic	**Addition**	Tomb	Neutron	Marines	**Division**	Anchor	Mathematical operation
Control	Trapeze	Orange	Corduroy	Tie	Masters	MorseCode	**Tractor**	Supper	Four-wheeled vehicle
Interference	Auburn	**Sofa**	Elation	Battalion	Rudder	**RockingChair**	Crime	Baritone	Furniture
Control	Scooter	Judicial	Asp	Gulf	Pipe	**Diving**	Squall	Fir	Water-sport
Interference	Square Root	Blue	**Wasp**	Garnet	Realtor	BassFishing	**Hornet**	Tanker	Insect that stings
Filler	Yogurt	Beret	**Walnut**	Aluminium					Nut
Interference	Snack	**Trunk**	Pickle	Capitalism	Nose Ring	**Bough**	Guppy	Ankle	Part of a tree
Control	Bible	Gerbil	Barge	Loud	Cumin	**Trampoline**	Sunset	Stem	Gymnastics event
Filler	Football	**Piranha**	Saxophone	Dynamite					Tropical fish
Interference	Cloves	Nephew	**Hamster**	Moped	Canal	Lime	**Guinea Pig**	Cellar	Rodent
Control	Topaz	Purple	Judge	Karate	Almanac	Cousin	**Rye**	Candle	Bread
Section 4									
Control	Paprika	Minute	Hourglass	Jack In The Box	Freight	**South**	Bark	Catfish	Direction
Interference	Cologne	**Pen**	Logic	Squirrel	Robbery	**Chalk**	Spinach	Tango	Writing implement
Control	Dime	Corporal	Molecule	Cabinet	Robin	Motor	**Marigold**	French Horn	Flower
Interference	Necklace	Surgeon	**Guitar**	Sirloin	Zinc	Slinky	**Piano**	Gopher	String instrument
Interference	Duchess	TNT	**Oak**	Rosary	Ginger	Kiwi	**Cedar**	Heron	Wood
Filler	Nose	**Cow**	Shirt	Dodo					Farm animal
Control	Frying Pan	Fudge	Wrench	Chlorine	Magenta	**Coal**	Blush	Cosmetic	Energy source
Control	Dentist	Brass	Sergeant	Gorgon	Crevasse	Macadamia	**Bridle**	Morphine	Horse-riding equipment
Interference	Sadness	Goat	**Cream**	Adjective	Monarchy	Rein	**Curd**	Quadrilateral	Dairy product
Control	Pencil	Coast Guard	Grape	Chandelier	Ostrich	**High Wire**	Cornet	Pumpernickel	Circus act
Interference	Biology	**Apple**	Summer	Train	Panther	**Cherry**	Sailfish	Closet	Fruit
Filler	Grave	Sink	**Love**	North					Emotion

Shape–Matching

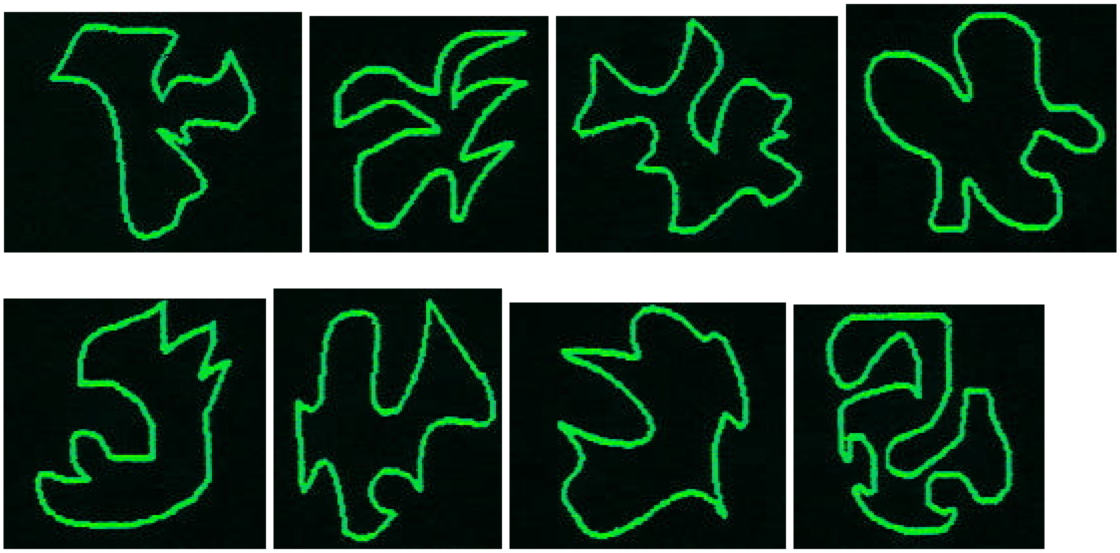
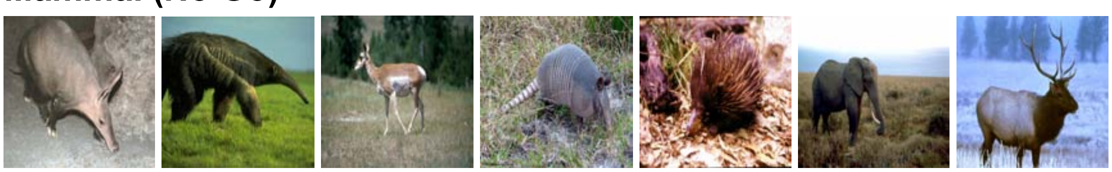


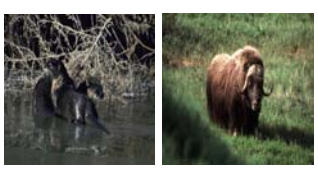
Figure A.1: Shapes used (equivalent red and white versions also used)

Go / No Go (picture) images

Mammal (No Go)



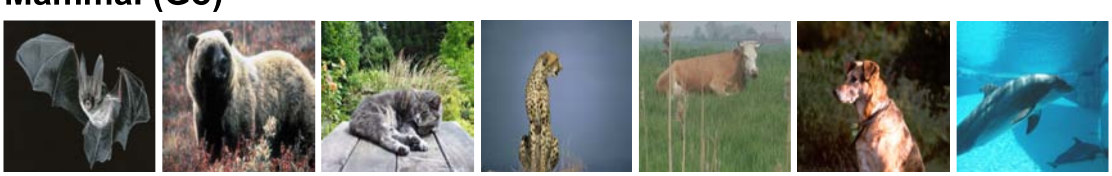
Aardvark Anteater Antelope Armadillo Echidna Elephant Elk



Otter Ox

Figure A.2: No Go mammal images

Mammal (Go)



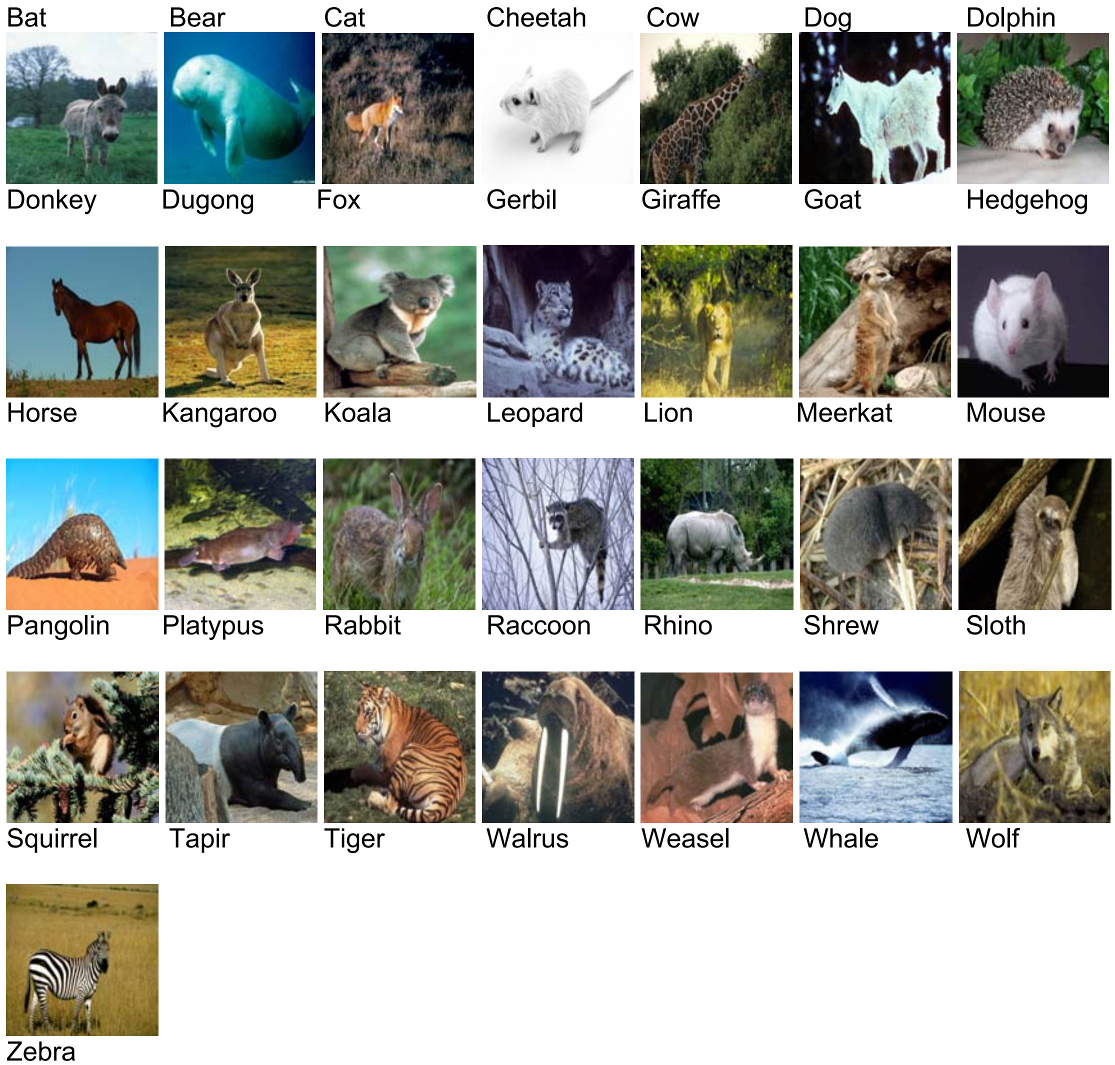


Figure A.3: Go mammal images

Bird (No Go)

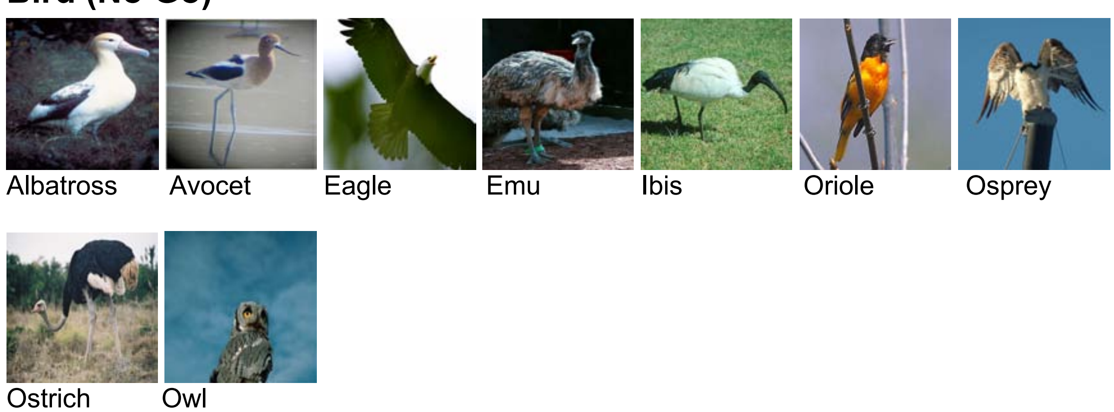


Figure A.4: No Go bird images

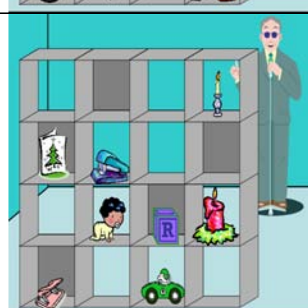
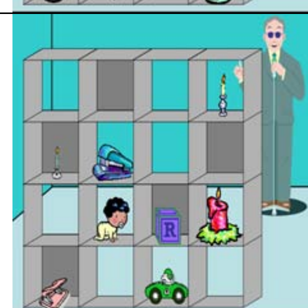
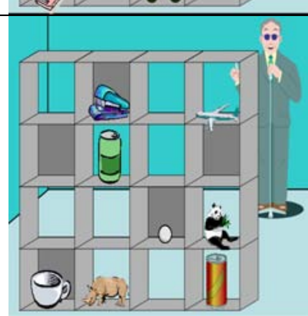
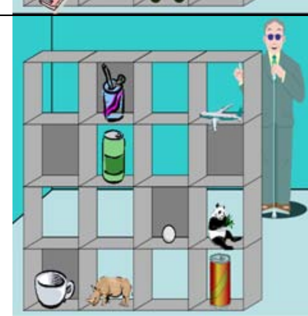
Bird (Go)

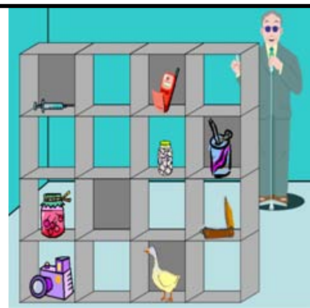
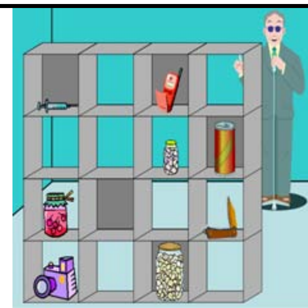
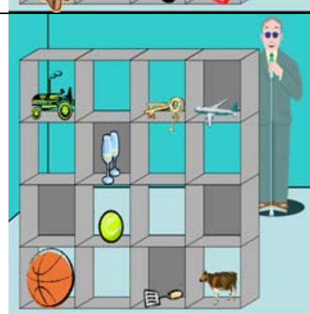
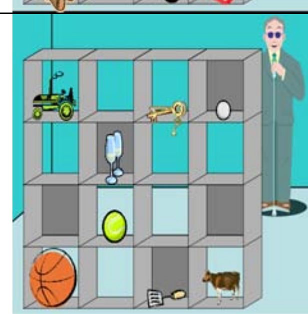
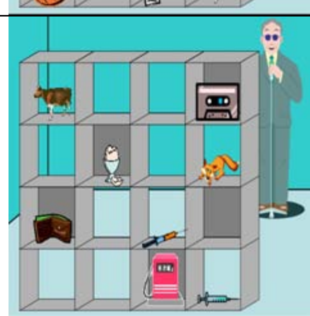
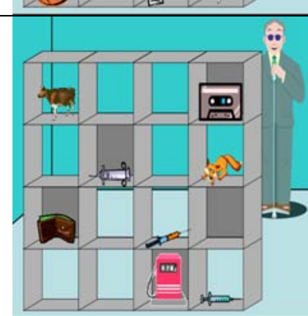
Figure A.5: Go bird images

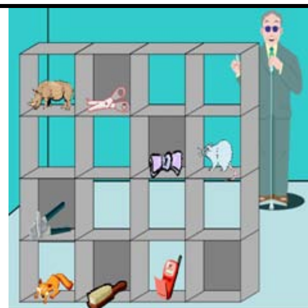
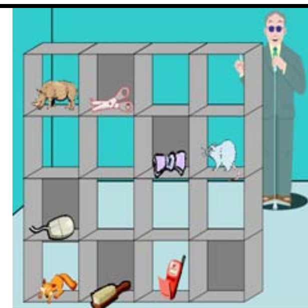
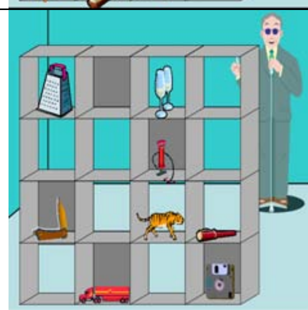
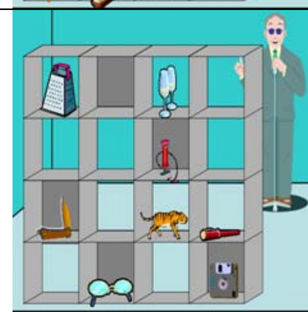
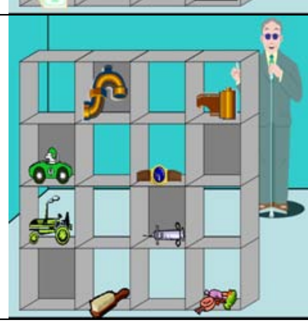
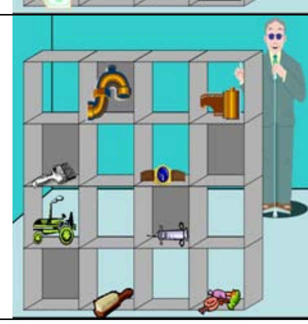
Keysar task grids and instructions

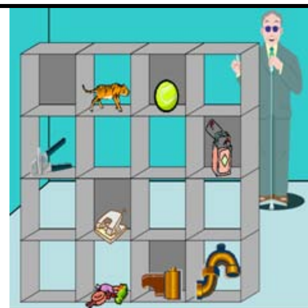
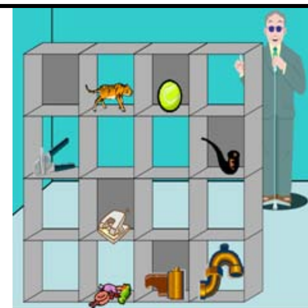
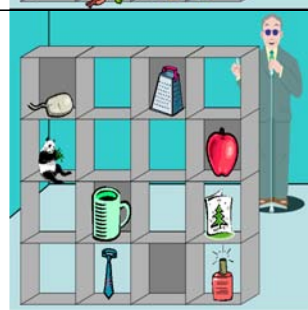
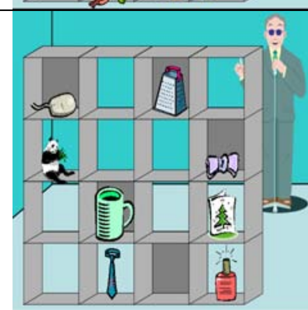
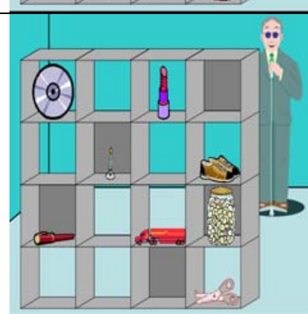
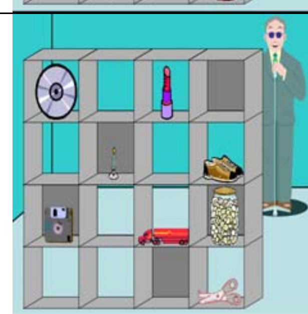
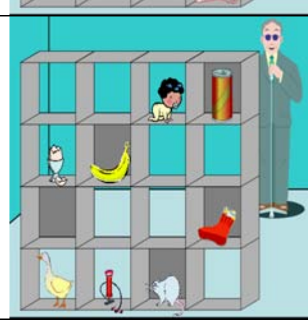
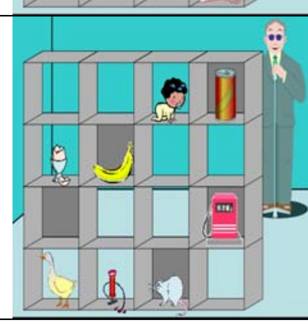
Table A.2

Critical Instructions and Grids for Keysar Task

Type	Critical instruction	Order	Control grid	Order	Experimental grid	Position of critical instruction / Total number of instructions
Relational	Move the bottom block left one slot	25		9		2 / 5
Relational	Move the large cup up one slot	17		29		3 / 3
Relational	Move the small candle down one slot	16		5		2 / 5
Relational	Move the top can right one slot	4		18		1 / 4

Type	Critical instruction	Order	Control grid	Order	Experimental grid	Position of critical instruction / Total number of instructions
Relational	Move the large jar right one slot	23		28		2 / 5
Relational	Move the bottom hole-punch down one slot	30		22		3 / 4
Relational	Move the small ball down one slot	10		2		3 / 4
Relational	Move the top syringe left one slot	1		12		2 / 3

Type	Critical instruction	Order	Control grid	Order	Experimental grid	Position of critical instruction / Total number of instructions
Ambiguous	Move the mouse down one slot	14		31		3 / 4
Ambiguous	Move the glasses right one slot	27		7		1 / 3
Ambiguous	Move the tape left one slot	13		3		3 / 3
Ambiguous	Move the brush up one slot	19		26		1 / 3

Type	Critical instruction	Order	Control grid	Order	Experimental grid	Position of critical instruction / Total number of instructions
Ambiguous	Move the pipe up one slot	21		11		4 / 4
Ambiguous	Move the tie left one slot	8		20		4 / 5
Ambiguous	Move the disc right one slot	6		15		1 / 4
Ambiguous	Move the pump up one slot	32		24		4 / 5

Appendix B

An alternate way of factoring out the common variance of the control and interference cued recall trials is to use the cued recall control measure to predict the cued recall interference measure, leaving the proactive interference or cognitive interference in the model. The following models are identical to those in the main chapters, except with the alternative method of factoring out the common variance of the control and interference cued recall measures.

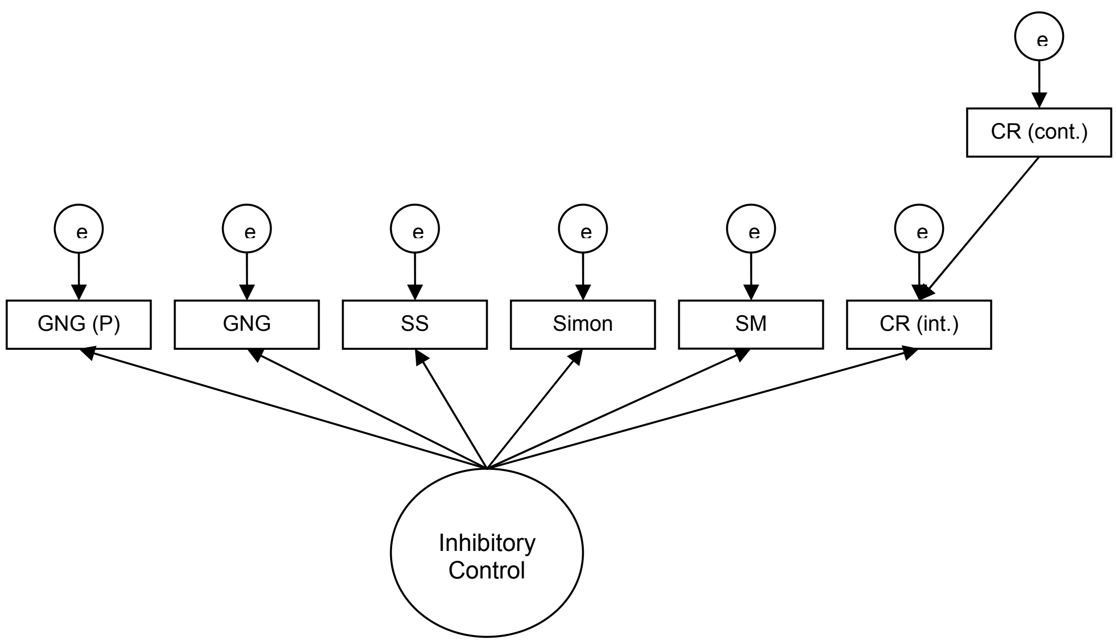


Figure B.1: One factor model

Table B.1

Path Estimates for One Factor Model

Parameters	Unstandardised Estimate[a]	S.E.[b]	*p*[c]	Standardised Estimate[d]
Direct effects				
Go / No Go (P)	0.98	0.52	0.06	0.35
Go / No Go	1.90	1.16	0.10	0.67
Stop Signal	1.00			0.27
CR int. (to IC)	0.46	0.31	0.14	0.16
CR control (to int.)	0.64	0.06	<0.01	0.67
Simon	0.65	0.43	0.13	0.22
Shape Matching	0.17	0.41	0.68	0.05

Parameters	Unstandardised Estimate[a]	S.E.[b]	p^c	Standardised Estimate[d]
Variance				
Inhibition	0.72	1.12	0.26	

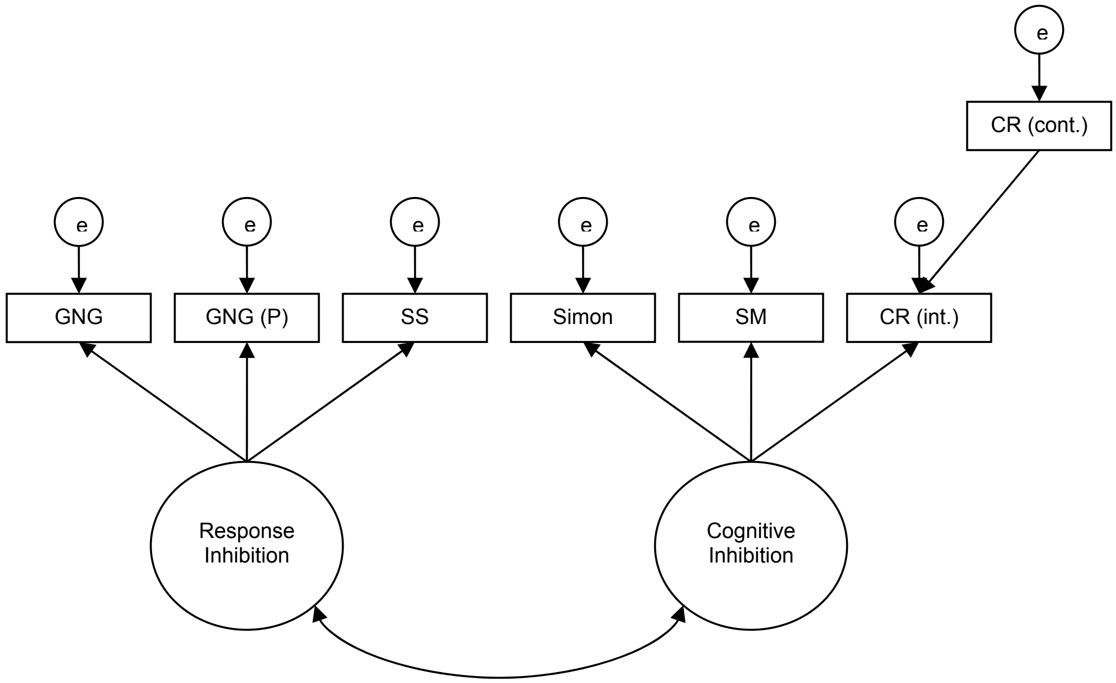


Figure B.2: Two factor model (RI and CI)

Table B.2

Path Estimates for Response and Cognitive Inhibition Model

Parameters	Unstandardised Estimate	S.E.	p	Standardised Estimate
Direct effects				
Go / No Go → Response	2.11	1.40	0.13	0.70
Go / No Go (P) →Response	0.99	0.53	0.06	0.33
Stop Signal → Response	1.00			0.26
CR int. → Cognitive	0.69	0.51	0.17	0.19
CR control → CR int.	0.65	0.06	<0.01	0.67
Simon → Cognitive	1.00			0.28
Shape Matching → Cognitive	0.16	0.58	0.27	0.04
Variances and covariances				
Response	0.65	0.61	0.29	
Cognitive	0.50	0.65	0.45	
Response ↔ Cognitive	0.43	0.34	0.20	0.76

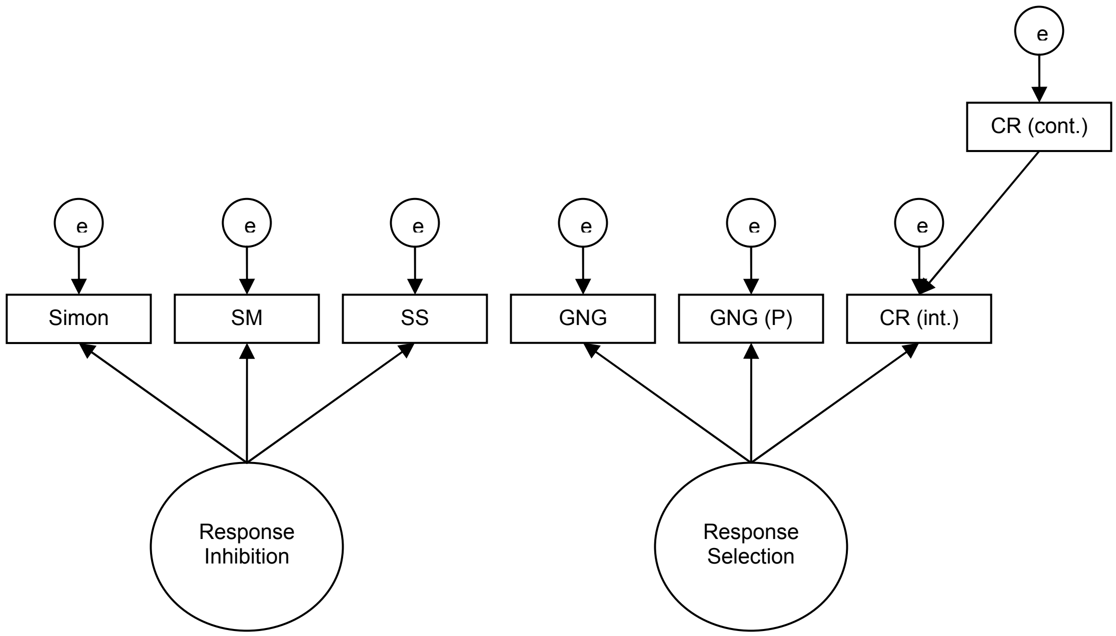


Figure B.3: Two factor model (RI and RS)

This configuration of the tasks did not fit the data, resulting in unexpected negative error variances. An alternate configuration of response inhibition and selection tasks was then chosen. As can be seen in the initial 1 factor model (Table B.1), the shape matching task had the lowest parameter estimate, so a two factor model with shape matching loading onto one latent variable was analysed (Figure B.4).

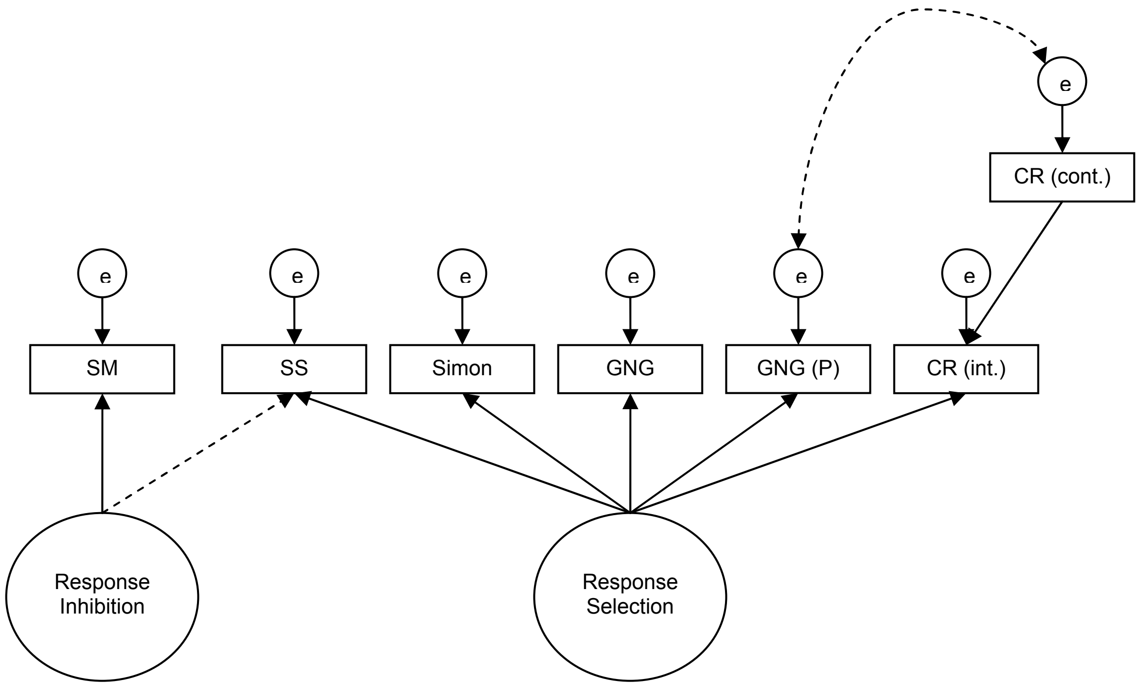


Figure B.4: Two factor model (SM on one factor)

Table B.3

Path Estimates for Alternate Response Inhibition and Selection Model

Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
Direct effects				
Go / No Go → Response Selection	1.00			0.73
Go / No Go (P) →Response Selection	0.44	0.28	0.11	0.32
CR int. → Response Selection	0.22	0.16	0.17	0.15
CR control → CR int.	0.65	0.06	<0.01	0.67
Simon → Response Selection	0.30	0.22	0.17	0.21
Stop Signal → Response Selection	0.43	0.29	0.14	0.25
Shape Matching → Response Inhibition	1.00			0.79
Variances and covariances				
Response Selection	3.10	1.94	0.11	
Response Inhibition	5.69	1.07	<0.01	

The modification indices calculated by AMOS suggested including a path from the stop – signal task to the response inhibition variable would significantly improve the fit of the model, and considering the theoretical basis for this path (that the stop – signal task requires both response inhibition and response selection), the path was added to the model. This resulted in the following set of parameter estimates (Table B.4).

Alternatives for this path include a covariance between the error terms of the shape matching and the stop – signal tasks or a covariance between the latent variables of response inhibition and response selection. These give identical values for the model fit (and equivalent parameter estimates) and the path between the stop – signal and the response inhibition latent variable was chosen as it allowed the variance to be explained by the model (in the case of the alternative covariances, the variance they account for is unexplained by the model), and as it is based on theoretical grounds too. This path is shown by the dashed arrow in Figure B.4.

Table B.4

Parameter Estimates Including Path from Stop - Signal to Response Inhibition

Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
Direct effects				
Go / No Go → Response Selection	1.00			0.77
Go / No Go (P) →Response Selection	0.39	0.26	0.13	0.30
CR int. → Response Selection	0.20	0.15	0.18	0.15
CR control → CR int.	0.65	0.06	<0.01	0.67
Simon → Response Selection	0.27	0.20	0.18	0.20
Stop Signal → Response Selection	0.40	0.28	0.16	0.24
Stop Signal → Response Inhibition	0.28	0.13	0.04	0.22
Shape Matching → Response Inhibition	1.00			0.79
Variances and covariances				
Response Selection	3.44	2.23	0.12	
Response Inhibition	5.69	1.07	<0.01	

The modification indices calculated by AMOS further suggested adding a covariance between the error terms of the cued recall control trials measure and the go / no go (picture) task. The parameter estimates for this model are below (Table B.5). The covariance indicates that there is some unexplained variance common to the cued recall control and go / no go (picture) measure. As both tasks may rely to some extent on working memory, it is possible that this is the variance in common. This covariance is shown by the curved dashed arrow in Figure B.4.

Table B.5

Parameter Estimates for Figure B.4 (with Covariance between CR Control and GNG P Error Terms)

Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
Direct effects				
Go / No Go → Response Selection	1.00			0.78
Go / No Go (P) →Response Selection	0.35	0.25	0.16	0.27
CR int. → Response Selection	0.20	0.15	0.21	0.15
CR control → CR int.	0.64	0.06	<0.01	0.67
Simon → Response Selection	0.26	0.21	0.21	0.20
Stop Signal → Response Selection	0.39	0.29	0.18	0.24
Stop Signal → Response Inhibition	0.28	0.13	0.04	0.22
Shape Matching → Response Inhibition	1.00			0.79
Variances and covariances				
e3 (gng p) ↔ e7 (cr control)	-1.30	0.51	0.01	-0.22
Response Selection	3.54	2.43	0.15	
Response Inhibition	5.69	1.07	<0.01	

The error variances of the tasks were all significantly different from zero apart from that of the go / no go task. Therefore the error variance of this task was constrained to zero for the final model. This resulted in the following set of parameter estimates (Table B.6).

Table B.6

Parameter Estimates for Figure B.4 (Error Variance of GNG Constrained to Zero)

Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
Direct effects				
Go / No Go → Response Selection	1.00			1.00
Go / No Go (P) →Response Selection	0.21	0.08	<0.01	0.21
CR int. → Response Selection	0.12	0.06	0.06	0.11
CR control → CR int.	0.64	0.06	<0.01	0.70
Simon → Response Selection	0.17	0.08	0.05	0.16
Stop Signal → Response Selection	0.23	0.10	0.03	0.18
Stop Signal → Response Inhibition	0.29	0.13	0.03	0.22
Shape Matching → Response Inhibition	1.00			0.79
Variances and covariances				
e3 (gng p) ↔ e7 (cr control)	-1.31	0.51	0.01	-0.22
Response Selection	5.78	0.67	<0.01	
Response Inhibition	5.69	1.07	<0.01	

The final four models are nested within each other, and so the model fit statistics can be compared. The statistics show that adding the path from the stop-signal task to the response inhibition latent variable significantly improved the model fit (X^2 change = 4.402, df change = 1, *p* = .036). Adding the covariance between the error terms of the cued recall control and go / no go (picture) tasks also significantly improved the model fit (X^2 change = 6.820, df change = 1, *p* = .009). Constraining the error variance of the go / no go task (effectively removing a parameter estimate) did not significantly affect the fit of the model (X^2 change = 0.368, df change = 1, *p* = .544).The fit of the final model can not be compared to the one factor or response inhibition / cognitive inhibition model using a chi-square difference test, but looking at the AIC statistic shows that the preferred model is the final model (with the lowest AIC value).

Table B.7

Model Fit Statistics

Model	X^2	df	*p*	NFI	CFI	AIC	RMSEA	Low	High
1 factor	21.70	14	0.09	0.83	0.93	49.70	0.06	0.00	0.11
2 factor: Response and Cognitive Inhibition	21.57	13	0.06	0.83	0.92	51.57	0.07	0.00	0.12
2 factor (alternate response inhibition and selection)	21.78	15	0.11	0.83	0.94	47.78	0.06	0.00	0.10
2 factor (path from stop – signal to response inhibition added)	17.38	14	0.24	0.87	0.97	45.38	0.04	0.00	0.09
2 factor (covariance between CR int. and go / no go (picture) error terms)	10.56	13	0.65	0.92	1.00	40.56	0.00	0.00	0.07
2 factor (gng error variance constrained to 0).	10.93	14	0.69	0.92	1.00	38.93	0.00	0.00	0.06

Chi-square values that are not significant (α = 0.05) indicate a reasonable fit to the data. Values of NFI over 0.9 indicate a reasonable fit to the data. Values of CFI close to 1.0 indicate a good fit to the data. Values of RMSEA that have a lower bound less than 0.05 and a higher bound less than 0.10 show good approximate fit (and do not show poor approximate fit). Hoelter gives the sample size at which the model could be rejected.

CFA Model

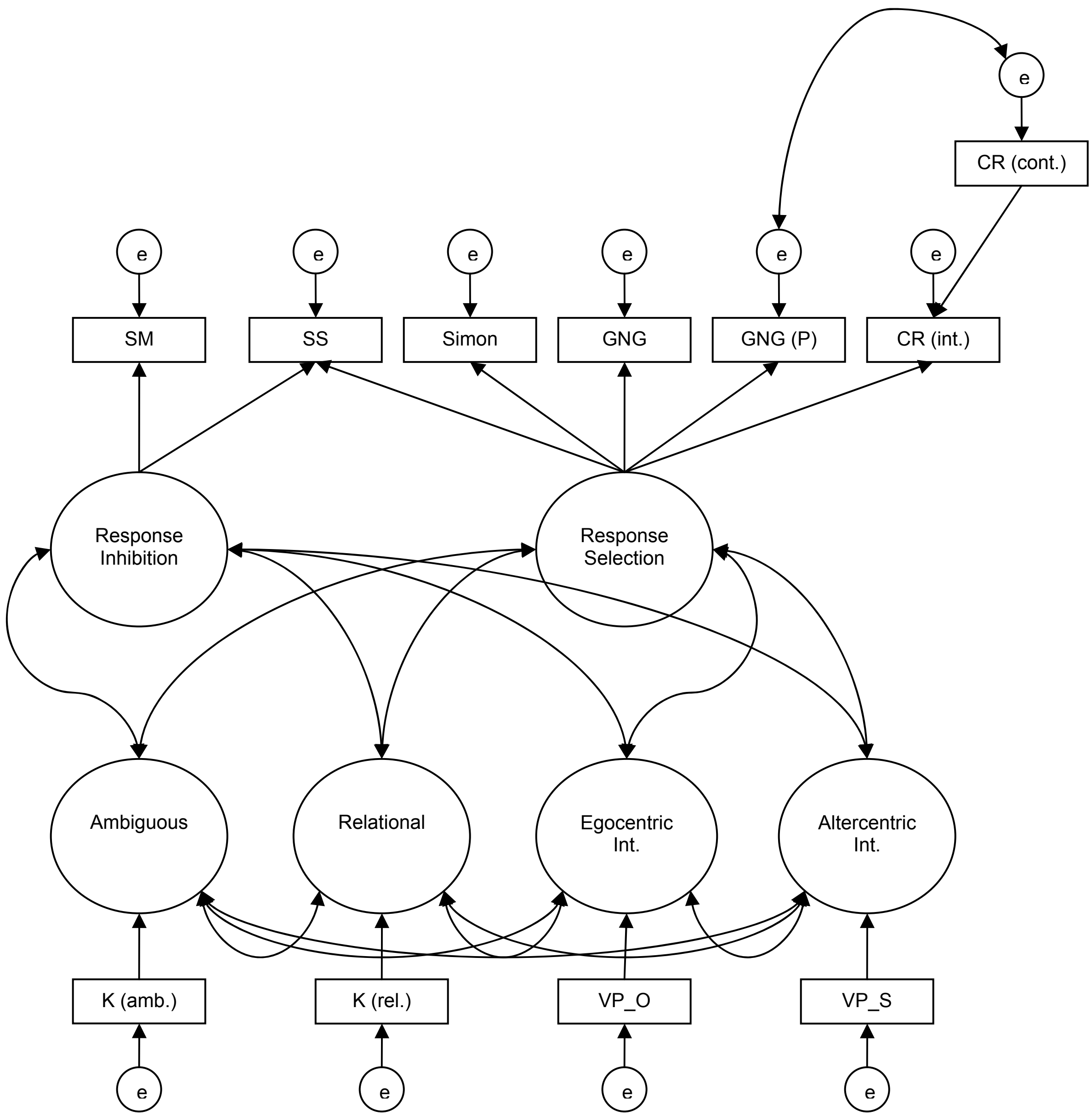


Figure B.5: CFA model

Model 1

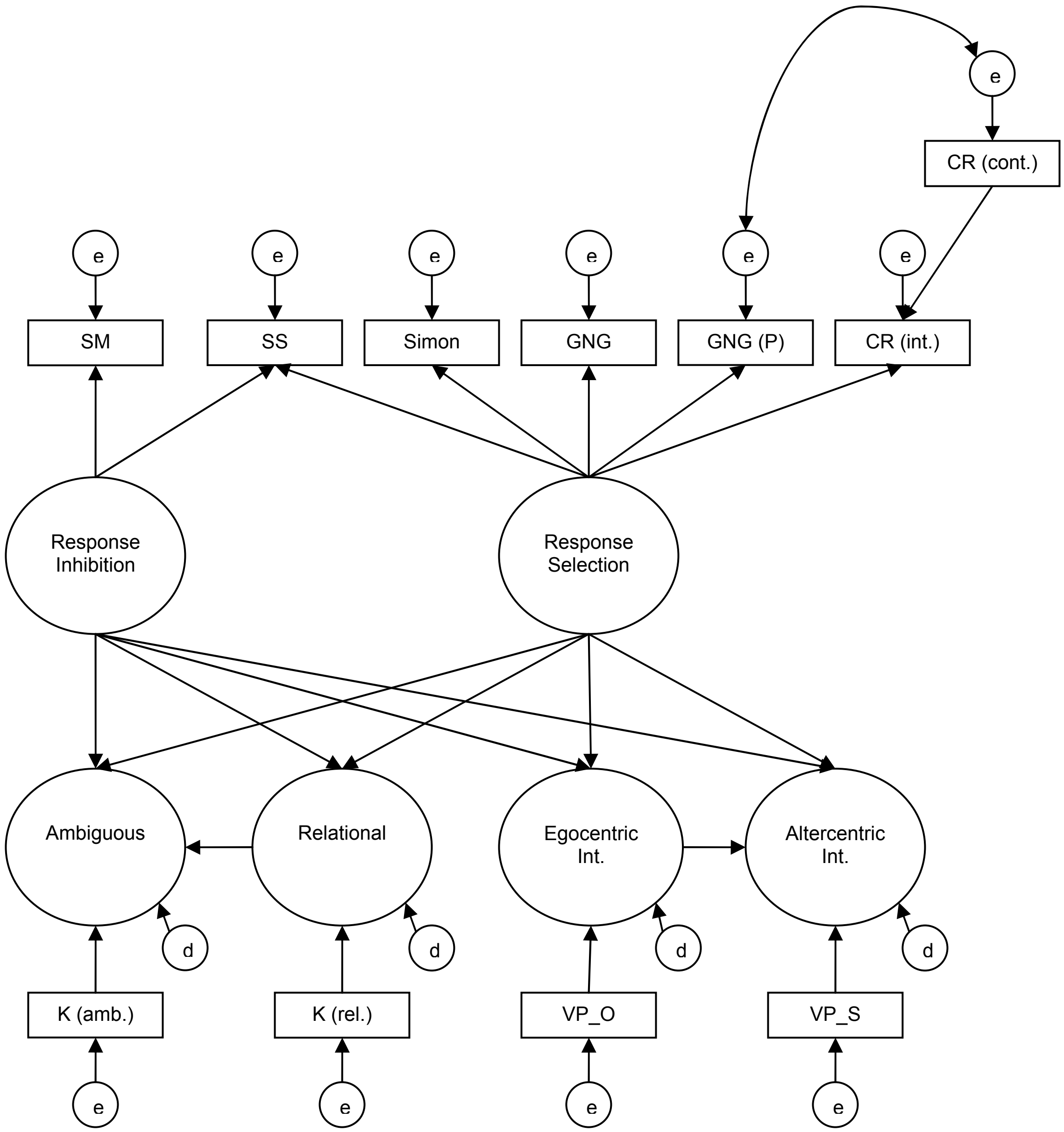


Figure B.6: Direct paths

Table B.8

All Paths

Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
Direct effects				
Relational → RI	0.26	0.12	0.03	0.24
Ambiguous → RI	-0.10	0.11	0.35	-0.11
Egocentric int. → RI	0.45	0.15	<0.01	0.38
Altercentric int. → RI	0.16	0.15	0.29	0.19
Relational → RS	-0.01	0.10	0.89	-0.01
Ambiguous → RS	0.01	0.08	0.87	0.02
Egocentric int. → RS	0.18	0.12	0.12	0.16
Altercentric int. → RS	0.05	0.11	0.62	0.06
Rel. → Amb.	0.86	0.09	<0.01	0.98[1]
Ego. Int. → Alt. Int.	0.26	0.13	0.05	0.35
Variances and covariances				
RS	5.78	0.67	<0.01	
RI	5.68	1.07	<0.01	
Squared Multiple Correlations (SMC)				
Relational	0.06			
Ambiguous	0.93			
Ego. Interference	0.17			
Alt. Interference	0.22			

[1] As this estimate is above 0.7, an interpretation is that these two latent variables are in fact the same. In order to test this, models with one latent variable for the Keysar task were tested (with ambiguous and relational errors as indicators). The statistics suggest that in the all path models, the one Keysar LV model is preferred, but in the significant path only models, the individual measure Keysar LVs are preferred (see appendix C).

Model 2

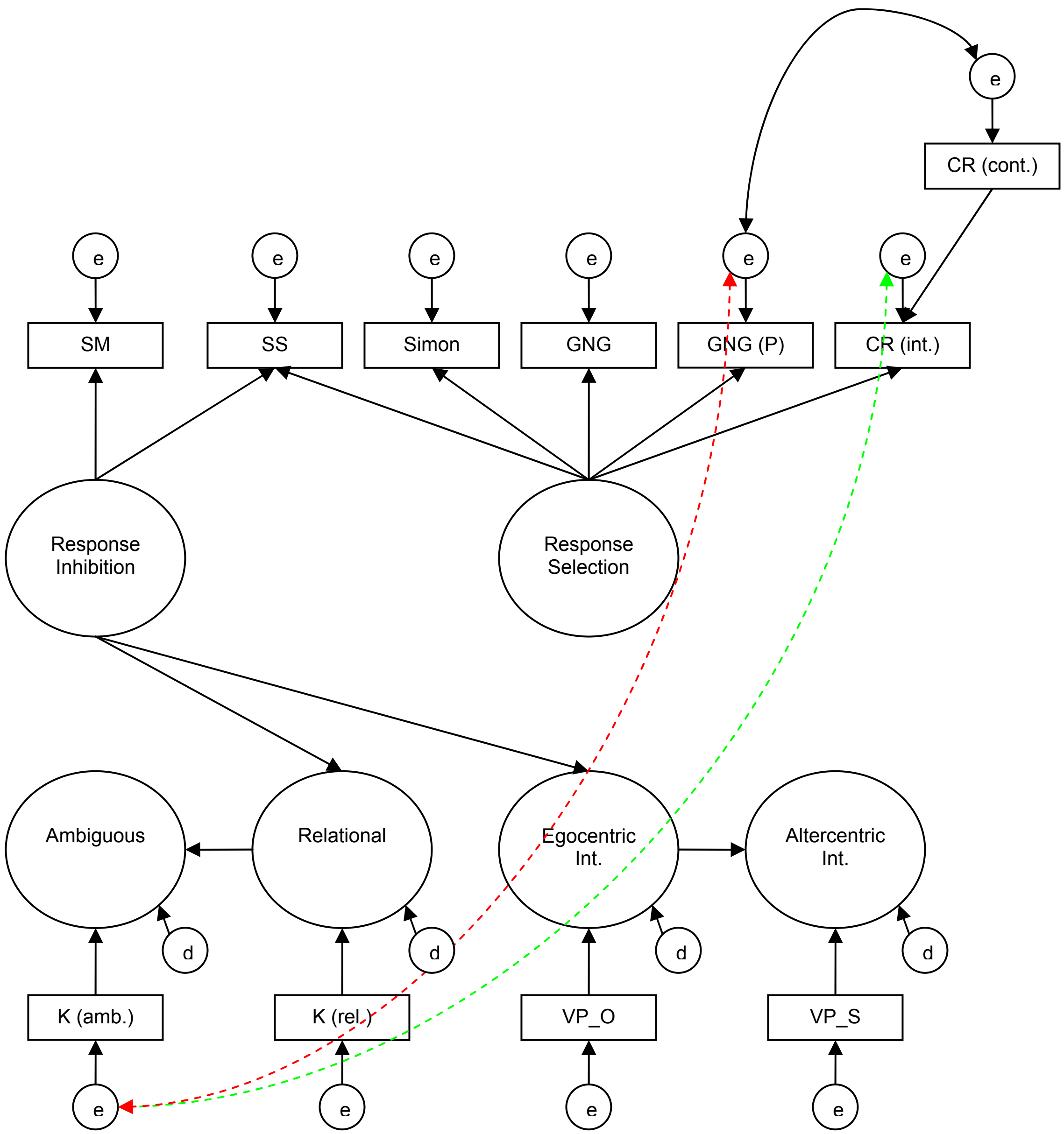


Figure B.7: Significant paths only

Table B.9

Significant Paths Only

Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
Direct effects				
Relational → RI	0.25	0.12	0.04	0.23
Egocentric int. → RI	0.46	0.15	<0.01	0.39
Rel. → Amb.	0.84	0.09	<0.01	0.96
Ego. → Alt.	0.33	0.11	<0.01	0.45
Variances and covariances				
RS	5.78	0.67	<0.01	
RI	5.67	1.07	<0.01	
Square Multiple Correlation				
Relational	0.05			
Ambiguous	0.91			
Ego. Interference	0.15			
Alt. Interference	0.21			

Model 3

The modification indices suggested adding a covariance from the error term of the cued recall interference measure to the error term of the ambiguous errors task would significantly improve the model fit. As the model was designed only to measure inhibitory control as the construct of interest, the covariance suggest the presence of another construct that is unexplained by the current model (covariance in a SR model indicated shared unexplained variance between the two variables involved). It is likely that inhibitory control is not the only executive function or theoretical construct that is related to or part of theory of mind, so the covariance was added to the model. This covariance is shown by the dashed curved green line in Figure B.7.

Table B.10

Path Model with Covariance between CR and Ambiguous Errors Added

Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
Direct effects				
Relational → RI	0.25	0.12	0.04	0.22
Egocentric int. → RI	0.46	0.15	<0.01	0.34
Rel. → Amb.	0.80	0.08	<0.01	0.99
Ego. → Alt.	0.33	0.11	<0.01	0.45
Variances and covariances				
e CR ↔ e Amb.	-1.18	0.38	<0.01	-0.30
RS	5.78	0.67	<0.01	
RI	5.67	1.07	<0.01	
Squared Multiple Correlations				
Relational	0.05			
Ambiguous	0.89			
Ego. Interference	0.15			
Alt. Interference	0.21			

Model 4

The modification indices showed that adding a covariance between the go / nogo (picture) measure error term and the ambiguous errors task error term would significantly improve the model fit. As the go / nogo (picture) and the cued recall task (which already covaried with the ambiguous errors error term) were correlated, it was likely that this covariance represented the same unexplained variance as the previous covariance. Therefore it was added to the model. This covariance is shown by the dashed curved red line in Figure B.7.

Table B.11

Path Model with Covariance between GNG (P) and Ambiguous Errors Added

Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
Direct effects				
Relational → RI	0.24	0.12	0.05	0.22
Egocentric int. → RI	0.46	0.15	<0.01	0.34
Rel. → Amb.	0.74	0.08	<0.01	0.92
Ego. → Alt.	0.33	0.11	<0.01	0.45
Variances and covariances				
e CR ↔ e Amb.	-1.25	0.37	<0.01	-0.31
e GNG (P) ↔ e Amb.	1.38	0.46	<0.01	0.27
RS	5.78	0.67	<0.01	
RI	5.67	1.07	<0.01	
Squared Multiple Correlations				
Relational	0.05			
Ambiguous	0.84			
Ego. Interference	0.15			
Alt. Interference	0.21			

At this point all the parameters included were significantly different from zero, and there were no parameters that would significantly improve the model fit that had a strong theoretical grounding. The model fits can all be seen in Table 6.6.

Table B.12

Model Fit Statistics

Model	CMIN	df	*p*	NFI	CFI	AIC	RMSEA	Low	High
CFA model	57.55	38	<0.01	0.80	0.90	121.55	0.07	0.04	0.10
All paths	59.56	38	0.01	0.78	0.91	115.56	0.06	0.03	0.09
Significant paths only	64.32	44	0.02	0.77	0.91	108.32	0.06	0.02	0.08
Sig. paths (add. cov.)*	53.78	43	0.13	0.81	0.95	99.78	0.04	0.00	0.07
Sig. paths (add. cov)**	44.60	42	0.36	0.84	0.99	92.60	0.02	0.00	0.06

*added covariance between error terms of cued recall interference measure and ambiguous errors measure
**added covariance between error terms of go / nogo (picture) measure and ambiguous errors measure

Error variances for EF factor models

Table B.13

Error Variances for One Factor Inhibition Model

Task	Unstandardised error variance	Standardised error variance
Go / No Go (P)	5.12**	0.88
Go / No Go	3.18*	0.55
Stop Signal	8.90**	0.93
Cued Recall (interference)	1.73**	0.28
Cued Recall (control)	2.36**	0.35
Simon	5.94**	0.95
Shape Matching	9.20**	0.10

* = significant at $p < 0.05$ for all tables

** = significant at $p < 0.01$ for all tables

Table B.14

Error Variances for Response and Cognitive Inhibition Model

Task	Unstandardised error variance	Standardised error variance
Go / No Go (P)	5.18**	0.89
Go / No Go	2.90 (ns)	0.50
Stop Signal	8.97**	0.93
Cued Recall (interference)	1.64**	0.26
Cued Recall (control)	2.36**	0.35
Simon	5.75**	0.92
Shape Matching	9.21**	0.99

Table B.15

Error Variances for Initial Response Inhibition and Selection Model

Task	Unstandardised error variance	Standardised error variance
Go / No Go (P)	5.30**	0.91
Go / No Go	2.24 (ns)	0.38
Stop Signal	8.59**	0.99
Cued Recall (interference)	1.74**	0.28
Cued Recall (control)	2.38**	0.35
Simon	6.01**	0.96
Shape Matching	6.85 (ns)	0.74

Table B.16

Error Variances for First Final Model

Task	Unstandardised error variance	Standardised error variance
Go / No Go (P)	5.23**	0.90
Go / No Go	2.68 (ns)	0.46
Stop Signal	9.04**	0.94
Cued Recall (interference)	1.73**	0.28
Cued Recall (control)	2.37**	0.35
Simon	5.97**	0.96
Shape Matching	3.53[2]	0.38

[2] Variance fixed using reliability value to identify model

Table B.17

Error Variances with Stop-Signal to RI Path Added

Task	Unstandardised error variance	Standardised error variance
Go / No Go (P)	5.29**	0.91
Go / No Go	2.34 (ns)	0.41
Stop Signal	8.64**	0.90
Cued Recall (interference)	1.74**	0.28
Cued Recall (control)	2.38**	0.35
Simon	5.99**	0.96
Shape Matching	3.53[2]	0.38

Table B.18

Error Variances for Final Model with Go / No Go Error Fixed at Zero

Task	Unstandardised error variance	Standardised error variance
Go / No Go (P)	5.50**	0.95
Go / No Go	0.00	1.00
Stop Signal	8.87**	0.92
Cued Recall (interference)	1.79**	0.29
Cued Recall (control)	2.41**	0.36
Simon	6.08**	0.97
Shape Matching	3.53[2]	0.38

Table B.19

Error Variances for Final Model with Covariance between CR Control and GNG (P)

Task	Unstandardised error variance	Standardised error variance
Go / No Go (P)	5.50**	0.95
Go / No Go	0.00	1.00
Stop Signal	8.87**	0.92
Cued Recall (interference)	1.89**	0.31
Cued Recall (control)	2.37**	0.36
Simon	6.08**	0.97
Shape Matching	3.53[2]	0.38

Error variances for ToM disturbances

Table B.20

Error Covariances for All Paths between inhibitory and ToM Factors Model

Task	Unstandardised error variance	Standardised error variance
d1 (amb)	0.39 (ns)	0.07
d2 (rel)	6.50**	0.94
d3 (ego)	6.62**	0.83
d4 (alt)	3.37**	0.78

Table B.21

Error Variances for Only Significant Paths between Inhibitory and ToM Factors Model

Task	Unstandardised error variance	Standardised error variance
d1 (amb)	0.47 (ns)	0.09
d2 (rel)	6.56**	0.95
d3 (ego)	6.68**	0.85
d4 (alt)	3.42**	0.80

Table B.22

Error Variances for Significant Paths Model with Covariance between CR (int) and Ambiguous Errors

Task	Unstandardised error variance	Standardised error variance
d1 (amb)	0.58 (ns)	0.12
d2 (rel)	6.56**	0.95
d3 (ego)	6.69**	0.85
d4 (alt)	3.42**	0.80

Table B.23

Error Variances for Significant Paths Only and Covariance between GNG (P) and Ambiguous Errors

Task	Unstandardised error variance	Standardised error variance
d1 (amb)	0.65 (ns)	0.15
d2 (rel)	6.57**	0.95
d3 (ego)	6.69**	0.85
d4 (alt)	3.42**	0.80

Table B.24

Error Variances for Aternate Final Model (Direct Paths to Ego- and Altercentric Factors)

Task	Unstandardised error variance	Standardised error variance
d1 (amb)	0.65 (ns)	0.15
d2 (rel)	6.59**	0.96
d3 (ego)	6.82**	0.86
d4 (alt)	3.89**	0.90

Appendix C

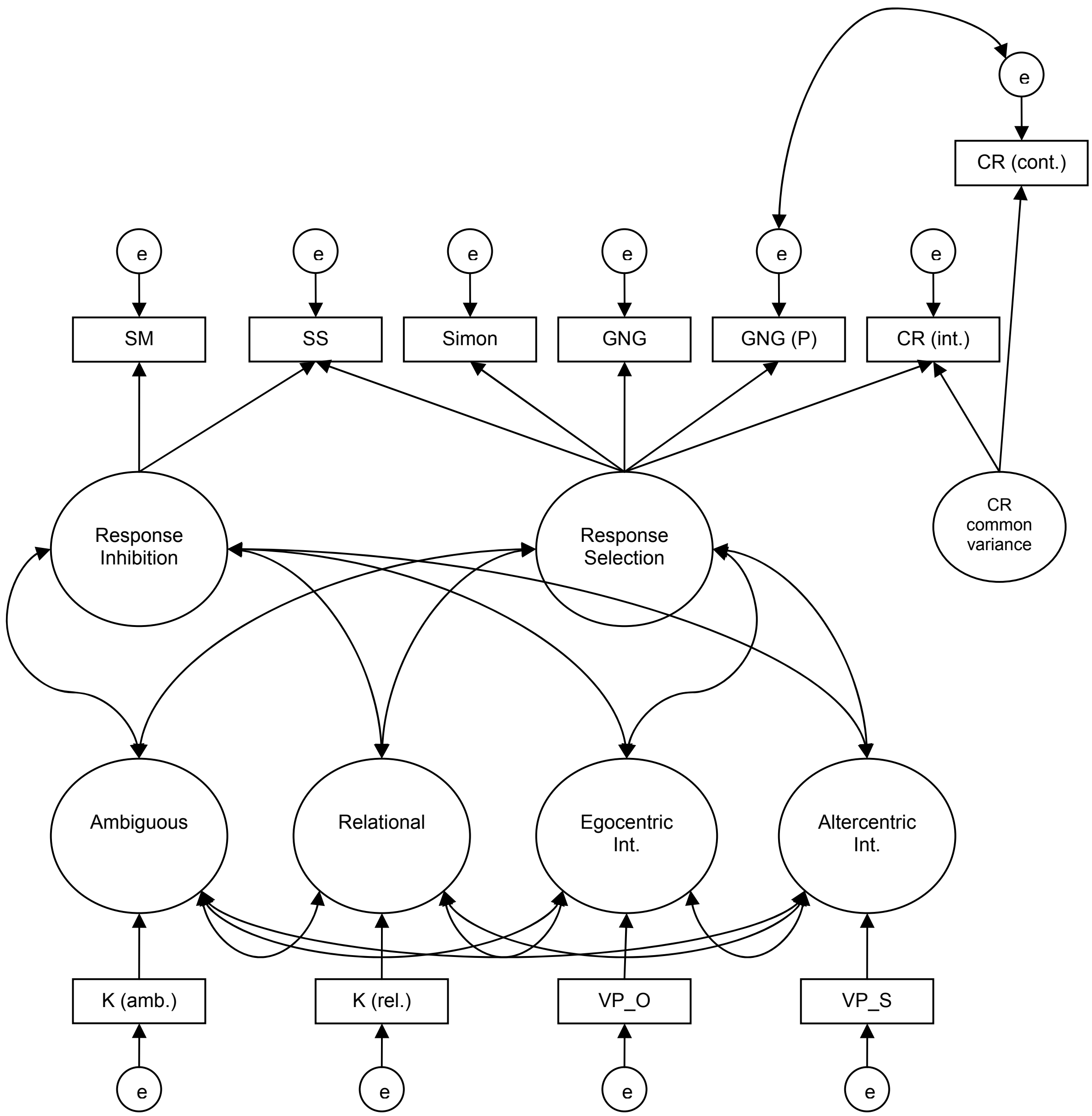


Figure C.1: CFA model (all paths)

As the covariance (and standardised correlation) between the ambiguous and relational measures of the Keysar task was < 0.7 in the models itself (although the correlation matrix calculated in Table 6.1 showed a correlation of > 0.7, which was why the model was first tested using separate latent variables for the ambiguous and relational errors), a model was tested in which the ambiguous and relational measures were indicators for one Keysar latent variable.

There was a relationship between the response inhibition latent variable and the Keysar latent variable (comparable with the relationship to the relational variable), and the relationship between the response inhibition latent variable and the egocentric interference latent variable. As the models could not be compared directly, the AIC values were compared. In Table C.1 the single Keysar latent variable model fit statistics are highlighted in yellow. The initial models, with all paths included, show that the single Keysar latent variable model is preferred. Once the non-significant paths are removed, the individual measure latent variable models are preferred. On this basis the individual measure latent variable models were chosen.

Table C.1

Model Fits for Individual Keysar Measure LVs Compared to Single Keysar LV

Model	CMIN	df	*p*	NFI	CFI	AIC	RMSEA	Low	High
CFA model	57.55	34	<0..01	0.80	0.90	121.55	0.07	0.04	0.10
CFA model (K)	62.75	40	0.01	0.78	0.90	114.75	0.06	0.03	0.10
All paths	59.56	38	0.01	0.79	0.91	115.56	0.06	0.03	0.09
All paths (K)	60.97	41	0.02	0.78	0.91	110.97	0.06	0.02	0.09
Significant paths only	64.32	44	0.02	0.77	0.91	108.32	0.06	0.02	0.08
Sig. paths only (K)	68.03	46	0.02	0.76	0.90	108.03	0.06	0.02	0.08
Sig. paths (add. cov.)*	53.78	43	0.13	0.81	0.95	99.78	0.04	0.00	0.07
Sig. paths (add. cov.)* (K)	59.48	45	0.07	0.79	0.94	101.48	0.05	0.00	0.08
Sig. paths (add. cov)**	44.60	42	0.36	0.84	0.99	92.60	0.02	0.00	0.06
Sig. paths (add. cov)** (K)	54.46	44	0.13	0.81	0.95	98.46	0.04	0.00	0.07

*added covariance between error terms of cued recall interference measure and ambiguous errors measure
**added covariance between error terms of go / nogo (picture) measure and ambiguous errors measure

LV = Latent variable

Appendix D

Model A

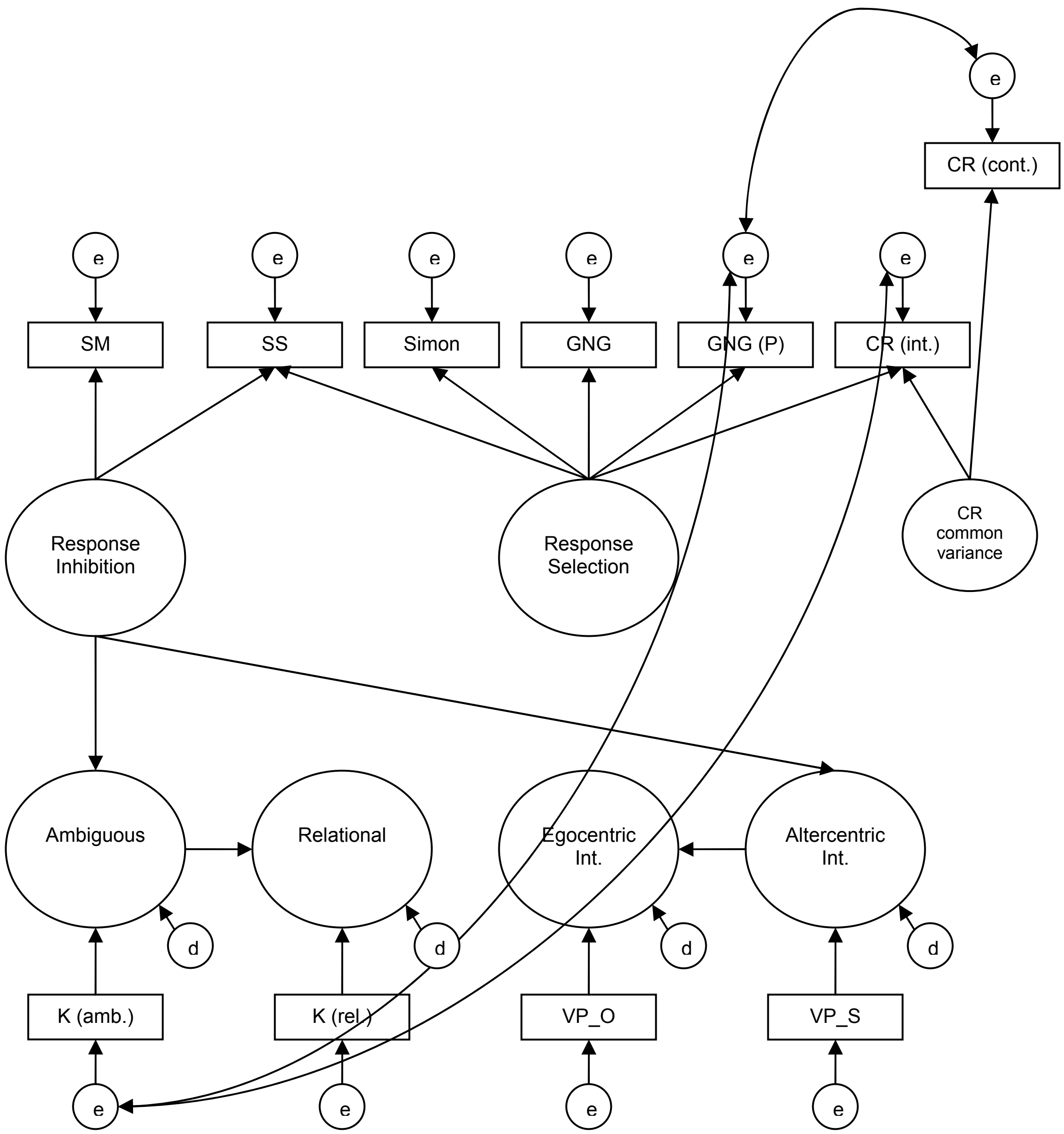


Figure D.1: Alternate RI to ToM paths

Table D.1

Parameter Estimates for Alternate RI - ToM Paths

Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
Direct effects				
Ambiguous ← RI	0.17	0.10	0.09	0.20
Altercentric ← RI	0.35	0.13	<0.01	0.41
Amb. → Rel.	1.24	0.21	<0.01	0.96
Alt. → Ego.	0.72	0.24	<0.01	0.51
Variances and covariances				
e CR ↔ e Amb.	-1.08	0.37	<0.01	-0.36
e GNG (P) ↔ e Amb	1.16	0.46	0.01	0.23
RS	5.78	0.67	<0.01	
RI	5.67	1.07	<0.01	
Residual	4.19	0.61	<0.01	
Squared Multiple Correlations				
Relational	0.93			
Ambiguous	0.04			
Ego. Interference	0.27			
Alt. Interference	0.17			

Model B

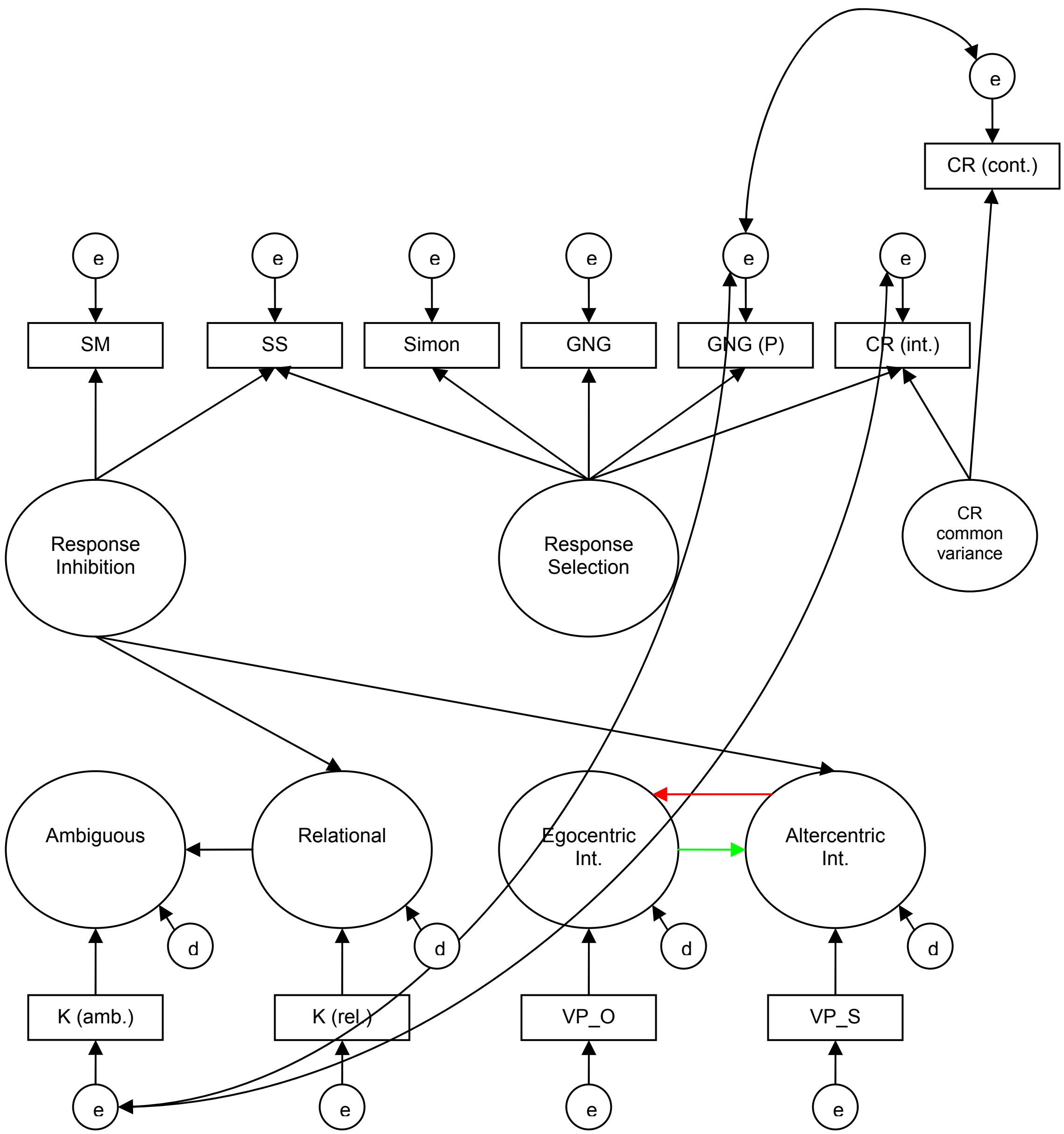


Figure D.2: Alternate paths between visual perspective latent variables

Table D.2

Egocentric to Altercentric Path Model Parameter Estimates (Green Arrow)

Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
Direct effects				
Relational ← RI	0.24	0.12	0.05	0.22
Altercentric ← RI	0.19	0.13	0.16	0.22
Rel. → Amb.	0.73	0.08	<0.01	0.98
Ego. → Alt.	0.28	0.11	0.01	0.38
Variances and covariances				
e CR ↔ e Amb.	-1.15	0.38	<0.01	-0.38
e GNG (P) ↔ e Amb	1.24	0.47	<0.01	0.24
RS	5.78	0.67	<0.01	
RI	5.67	1.07	<0.01	
Residual	4.19	0.61	<0.01	
Squared Multiple Correlations				
Relational	0.05			
Ambiguous	0.85			
Ego. Interference	0.00			
Alt. Interference	0.20			

Table D.3

Altercentric to Egocentric Path Model Parameter Estimates (Red Arrow)

Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
Direct effects				
Relational ← RI	0.23	0.12	0.06	0.21
Altercentric ← RI	0.35	0.13	<0.01	0.41
Rel. → Amb.	0.73	0.08	<0.01	0.92
Ego. ← Alt.	0.72	0.24	<0.01	0.52
Variances and covariances				
e CR ↔ e Amb.	-1.15	0.38	<0.01	-0.38
e GNG (P) ↔ e Amb	1.24	0.47	<0.01	0.24
RS	5.78	0.67	<0.01	
RI	5.67	1.07	<0.01	
Residual	4.19	0.61	<0.01	
Squared Multiple Correlations				
Relational	0.04			

Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
Ambiguous	0.85			
Ego. Interference	0.27			
Alt. Interference	0.17			

Model C

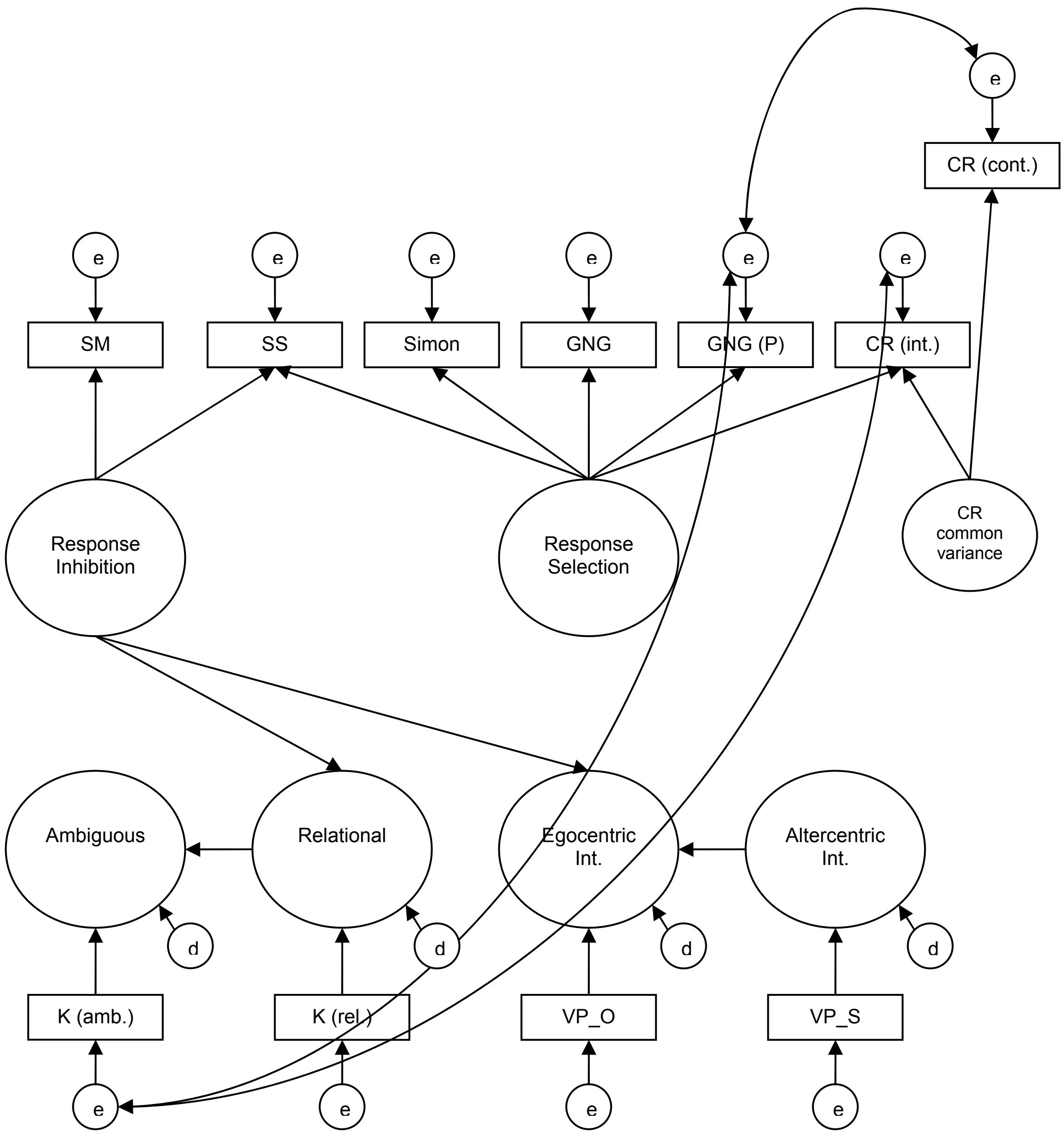


Figure D.3: RI - Egocentric model with altercentric to egocentric path

Table D.4

RI - Egocentric Model Parameter Estimates

Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
Direct effects				
Relational ← RI	0.25	0.12	0.04	0.23
Egocentric ← RI	0.38	0.15	0.01	0.33
Rel. → Amb.	0.73	0.08	<0.01	0.92
Ego. ← Alt.	0.50	0.22	0.02	0.37
Variances and covariances				
e CR ↔ e Amb.	-1.14	0.38	<0.01	-0.38
e GNG (P) ↔ e Amb	1.24	0.47	<0.01	0.24
RS	5.78	0.67	<0.01	
RI	5.68	1.07	<0.01	
Residual	4.19	0.61	<0.01	
Squared Multiple Correlations				
Relational	0.05			
Ambiguous	0.85			
Ego. Interference	0.24			
Alt. Interference	0.00			

Model D

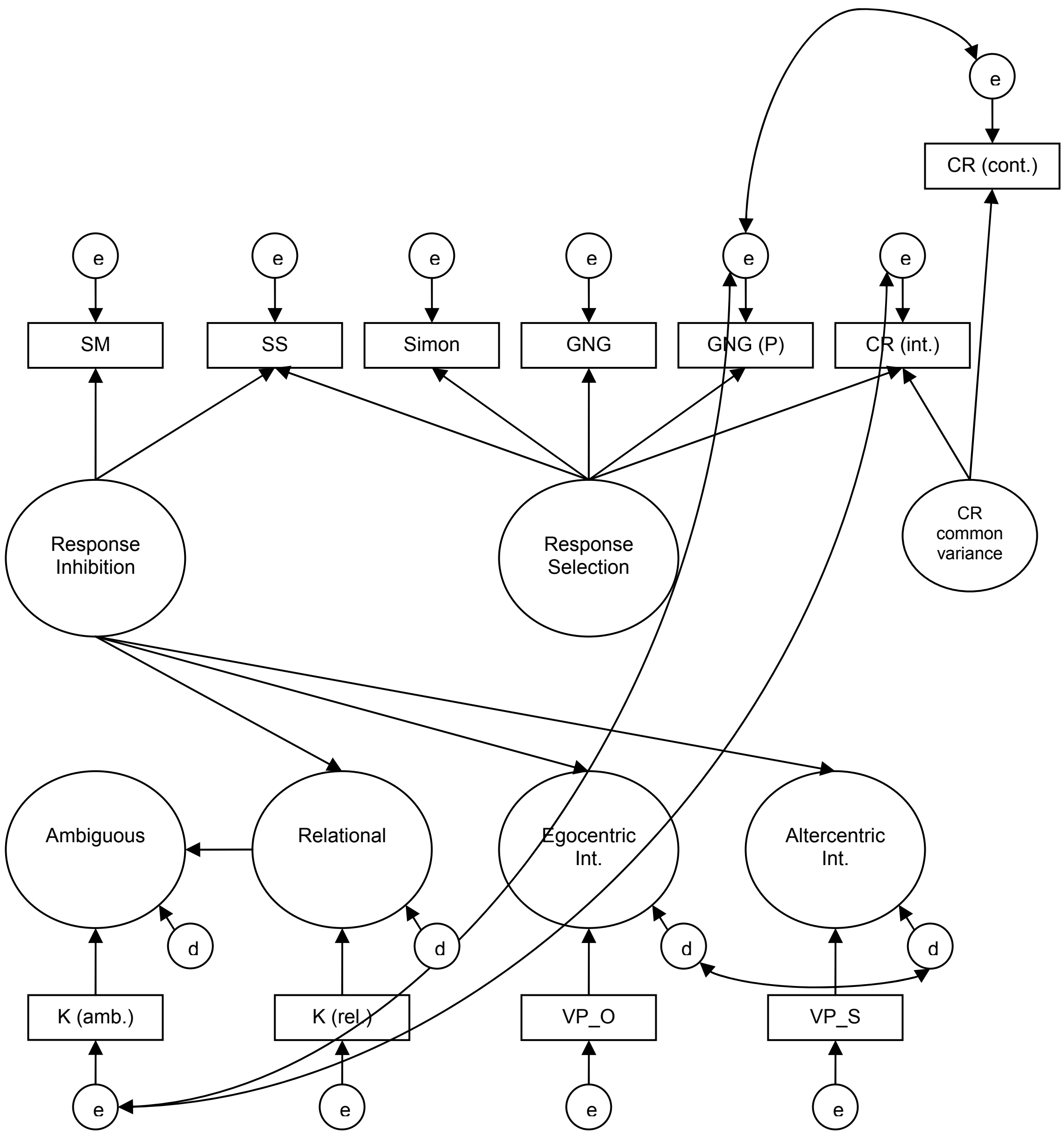


Figure D.4: Covariance between visual perspective latent variables model

Table D.5

Visual Perspective Covariance Model Parameter Estimates

Parameters	Unstandardised Estimate	S.E.	*p*	Standardised Estimate
Direct effects				
Relational ← RI	0.24	0.12	0.05	0.21
Egocentric ← RI	0.44	0.15	<0.01	0.37
Altercentric ← RI	0.27	0.14	0.05	0.31
Rel. → Amb.	0.73	0.08	<0.01	0.92
Variances and covariances				
d Ego. ↔ d Alt.	1.84	0.91	0.04	0.36
e CR ↔ e Amb.	-1.14	0.38	<0.01	-0.38
e GNG (P) ↔ e Amb	1.24	0.47	<0.01	0.24
RS	5.78	0.67	<0.01	
RI	5.67	1.07	<0.01	
Residual	4.19	0.61	<0.01	
Squared Multiple Correlations				
Relational	0.05			
Ambiguous	0.85			
Ego. Interference	0.14			
Alt. Interference	0.10			

Table D.6

Model Fit Statistics

Model	CMIN	df	*p*	NFI	CFI	AIC	RMSEA	Low	High
Model A	49.56	42	**0.20**	0.82	**0.97**	97.56	**0.04**	**0.00**	**0.07**
Model B (ego to alt)	54.23	42	**0.10**	0.81	**0.95**	102.23	**0.04**	**0.00**	**0.08**
Model B (alt to ego)	48.85	42	**0.22**	0.83	**0.97**	96.85	**0.03**	**0.00**	**0.07**
Model C	49.63	42	**0.20**	0.82	**0.97**	97.63	**0.04**	**0.00**	**0.07**
Model D	45.79	41	**0.28**	0.84	**0.98**	95.79	**0.03**	**0.00**	**0.07**
Final model (from chapter)	46.75	42	**0.28**	0.83	**0.98**	**94.75**	**0.03**	**0.00**	**0.06**