**CogWatch – Cognitive Rehabilitation of Apraxia and Action Disorganisation Syndrome**

# D1.2 Literature Review

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| Authors (per company, if more than one company provide it together) | | **Joachim Hermsdörfer (TUM), Alan Wing, Glyn Humphreys, Amy Arnold (UOB), Melanie Wulff (UOB), Georg Goldenberg (STKM)** | |
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## EXECUTIVE SUMMARY


The purpose of this deliverable is to give the background to the CogWatch project in which a rehabilitation system for cognitive impairments of sequential action will be developed.

In the Introduction the clinical features and the aetiology of apraxia and action disorganization syndrome are defined. The following literature review then concentrates on those aspects that are relevant for the realization of a cognitive rehabilitation system. Various relevant topics are highlighted including:

- Studies on the performance of apraxic patients during the use of single tools prove the existence of performance deficits even in seemingly simple tasks such as hammering or sawing.
- Goal-direct movements such as pointing or grasping can be impaired even in the hand ipsilateral to the lesion as has been shown in a number of studies.
- Although performance is often analysed in terms of categorising qualitative errors, quantitative approaches based on kinematics turn out to be highly sensitive in studies of actual tool use.
- Studies of multiple-step action with multiple tools and objects, typical of activities of daily living, have revealed particularly severe performance deficits in apraxic patients.
- Deficits that can be linked to apraxia and deficits that can be linked to action disorganization syndrome merge so that frequently no clear attribution to one of both syndromes is possible warranting, for the purposes of CogWatch, the conflation of the syndromes to “apraxia and action disorganization syndrome” (AADS).
- Error analyses reveal a great variety of different errors with increased occurrence of particular error types.
- The summary of various aspects of patients’ behaviour during tool related actions leads to a specification of requirements for a cognitive rehabilitation system.
- Various models of human sequential action, which can serve as action generation prototypes against which patients’ performance can be compared, have been devised to simulated performance in complex actions. These models might be implemented and tested in the CogWatch system.

On the basis of the summarized studies of cognitive rehabilitation in AADS, it is concluded that intervention by therapists can be successful. However, the review has brought forth only very few instances of ICT-based cognitive rehabilitation. Thus, while cognitive training of AADS symptoms by therapists has been proven successfully, approaches basing on automated systems using modern technology are missing which constitutes a real opportunity for CogWatch.

## TABLE OF CONTENTS


1. INTRODUCTION ........ 9

1.1 Apraxia ........ 9

1.1.1 Seminal descriptions ........ 9
1.1.2 Definition of apraxia ........ 9
1.1.3 Imitation of gestures ........ 10
1.1.4 Communicative gestures and pantomimes ........ 11
1.1.5 Use of single conventional tools and objects ........ 11
1.1.6 Multi-step actions ........ 12

1.2 Anatomical correlates ........ 13

1.2.1 Imitation of gestures ........ 13
1.2.2 Pantomimes ........ 13
1.2.3 Tool Use ........ 14
1.2.4 Multi-step action ........ 14
1.2.5 Callosal apraxia ........ 14

1.3 Theoretical accounts ........ 15

1.3.1 Imitation of gestures ........ 15
1.3.2 Pantomimes ........ 16
1.3.3 Use of single conventional tools and objects ........ 16
1.3.4 Multi step actions ........ 17
1.3.5 Ideational and ideo-motor apraxia ........ 18

1.4 Action Disorganisation Syndrome ........ 20

1.4.1 Definition ........ 20
1.4.2 Diagnosis and Action Coding System ........ 20
1.4.3 Error types and their frequency ........ 21
1.4.4 Mechanisms underlying ADS ........ 23
1.4.5 Norman-Shallice theory of attention and action ........ 23
1.4.6 Deficits in inhibition of action ........ 24
1.4.7 Resource deficits ........ 24
1.4.8 Deficits in error monitoring ........ 25

2. REVIEW OF THE LITERATURE (INCLUDING TESTING METHODS)....................... 26

2.1 Tool use....................................................................................................................26

2.1.1 Deficits during use of single tools ............................................................ 26

2.1.2 Movement execution during use of tools ................................................. 28

2.1.3 Execution of goal directed movements..................................................... 29

2.1.4 Multi Step Actions – Everyday tasks ......................................................... 30

2.1.5 Mechanical problem solving ..................................................................... 35

2.2 Activities of Daily Living and Apraxia.....................................................................36

2.3 Models of action selection......................................................................................37

2.3.1 Contention Scheduling Model – Norman and Shallice (1986)................................ 38

2.3.2 Interactive Activation Model (IAN): A computational model of the contention scheduling theory of routine action (Cooper and Shallice, 2000). ...................................... 39

2.3.3 Parallel Distributed Processing: Simple Recurrent Network. Botvinick and Plaut (2002, 2004)............................................................................................................... 41

2.3.4 Reinforcement Model of Routine Action – Ruh, Cooper and Mareschal (2005) .... 43

2.3.5 Adaptive Control of Thought Rational (ACT-R) – Byrne (2003) ............................ 45

2.3.6 Adaptation of the ACT-R architecture - Memory for Goals model (MFG) – Trafton (2011) 46

2.5 Approaches to rehabilitation .................................................................................48

3. CONCLUSIONS........................................................................................... 52

3.1 Publication strategy ................................................................................................54

4. REFERENCES............................................................................................. 55

## TABLE OF FIGURES

Figure 1 - Depiction of the two-route model of action selection (based on Rothi et al. 1997). ........ 15

Figure 2 - Example of how task performance of an ADS patient can be assessed relative to the basic steps for the task generated by normal participants. (From Humphreys & Forde, 1998)........ 21

Figure 3 - The distribution of errors by error type for patients with closed brain injury (CHI), right hemisphere stroke (RCVA) and left hemisphere stroke (LCVA). (From Schwartz, 2006). ........ 23

Figure 4 - Hierarchical representation of a tea making task (Humphreys & Forde, 1998). .. 37

Figure 5 - Horizontal thread from the Contention Scheduling System (Norman & Shallice, 1986)........ 38

Figure 6 - Vertical and horizontal threads (Norman & Shallice, 1986)........ 39

Figure 7 - The principal components of the contention scheduling implementation (Cooper & Shallice, 2000) ........ 40

Figure 8 - IAN processing architecture (Cooper & Shallice, 2000) ........ 41

Figure 9 - Architecture of the Simple Recurrent Network (Botvinick & Plaut, 2004) ........ 42

Figure 10 - Architecture of the Reinforcement Model (Ruh et al, 2005) ........ 44

Figure 11 - Major components of ACT-R (Byrne, 2003)........ 46

## TABLE OF TABLES

Table 1 - Summary of error types based on studies by Buxbaum, Schwartz and Montgomery (1998) and Schwartz and colleagues (1999a; 1998a). Note: (From Cooper, Schwartz, Yule, & Shallice, 2005)........ 22

Table 2 - Summary of reports on performance deficits during the use of actual tools following brain damage. ........ 26

Table 3 - Summary of reports analysing three-dimensional movement kinematics during tool-use in patients with brain damage ........ 28

Table 4 - Summary of studies of performance deficits during goal-directed movements with the ipsilesional hand in brain damaged patients ........ 29

Table 5 - Summary of reports on performance deficits in patients with ADS........ 31

Table 6 - Reports on deficits of mechanical problem solving in stroke patients........ 35

Table 7 - Features and actions specific to certain objects ........ 43

Table 8 - Summary of approaches for the cognitive rehabilitation of AADS ........ 49

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## LIST OF ABBREVIATIONS AND DEFINITIONS

| **Abbreviation** | Abbreviation |
|---|---|
| **CVA** | Cerebrovascular accident (stroke) |
| **ADS** | Action disorganisation syndrome |
| **ADL** | Activity of daily living |
| **LBD** | Left brain damage |
| **RBD** | Right brain damage |
| **AADS** | Apraxia and action disorganization syndrome |
| **CSS** | Contention scheduling system |
| **SAS** | Supervisory attention system |
| **ACS** | Action Coding System |
| **IAN** | Interactive Activation Model |
| **PDP** | Parallel distributed processing |
| **SRN** | Simple recurrent network |
| **ACT-R** | Adaptive control of thought rational |

# 1. INTRODUCTION

***CogWatch aims to improve patients' independence:***

It has been found that as many as 68% of stroke patients meet the criteria for Apraxia and Action Disorganization Syndrome (AADS; Bickerton, Samson, Williamson, & Humphreys, 2011). The difficulty these patients experience in sequencing everyday tasks means they are more dependent on caregivers and healthcare systems and means that they are frequently unable to live independently (Sunderland & Shinner, 2007). The purpose of this deliverable is to review the neurological and neuropsychological literature to identify effective assessment and rehabilitation practices for AADS. In addition, we will identify the most promising action organisation theories and experimental protocols that will be used to study AADS patients and which provide effective psychological models for action recognition.

In this introduction, the manifestations and concepts of apraxia and ADS will be presented in a broader context. In the core part of the deliverable only those aspects particularly relevant for CogWatch will be reviewed.

## 1.1 Apraxia

### 1.1.1 <u>Seminal descriptions</u>

Historically the first elaborate description of apraxia as a distinct neuropsychological syndrome was provided by Hugo Liepmann in the beginning of the nineteenth century (Liepmann, 1908). Liepmann's seminal writings have retained direct influence on research and theorizing on apraxia until today (Goldenberg, 2003a). He corroborated early anecdotal descriptions of defective use of communicative gestures and tools in aphasia through systematic exploration of both single cases and groups of brain damaged patients. The new clinical observation was that many patients also present with difficulties in the imitation of demonstrated gestures. His concept identified deficient motor control at the heart of an apraxic impairment. Liepmann proposed that there are apraxic patients who have a correct concept of what they ought to do but cannot transform the image of the intended action into appropriate motor commands. He noted in a group study comparing patients with right and left hemisphere damage that apraxia is associated with left brain damage (Liepmann, 1908). This notion led him to postulate a dominance of the left hemisphere for deliberate motor control above and beyond its dominance for language and speech.

Liepmann's model of motor control and the taxonomy of apraxia derived from that model have not withstood the test of hundred years of progress in neuropsychology. However, his understanding of apraxia as a disturbance at the interface between cognition and motor control still sets the stage upon which research on apraxia takes place.

### 1.1.2 <u>Definition of apraxia</u>

A widely accepted definition of apraxia describes it as a "disorder of skilled movement not caused by weakness, akinesia, deafferentiation, abnormal tone or posture, movement disorders (such as tremors or chorea), intellectual deterioration, poor comprehension, or uncooperativeness" (Heilman & Rothi, 1993). This definition reiterates Liepmann's postulate of a disturbance at the interface between cognition and motor control. As can be inferred from this definition by exclusion, the term apraxia has been used for disturbances of widely different actions ranging from lid closure and gait to dressing and spatial constructions. There is, however, a core of clinical manifestations which are generally accepted as supporting a diagnosis of apraxia. They concern three domains of human actions: (1) The imitation of gestures, (2) the performance of communicative gestures, and (3) the use of tools and objects. All of them occur predominantly after left brain lesions and are frequently, though not invariably, associated with aphasia. Another common point is that in contrast to genuine "motor" disturbances they affect not only the side of the body opposite to the cerebral lesion but also the ipsilateral side. Most of the actions considered in research on apraxia are manual, but some actions in each of the domains can also be observed at the legs, face or trunk.

### 1.1.3 Imitation of gestures

From a clinical point of view, testing imitation is attractive because of its essentially non-verbal nature, which liberates the examination from the confounding influence of comorbid aphasia. The independence from language is particularly obvious when imitation is tested for meaningless gestures which bear no verbal label.

Defective imitation will rarely be conspicuous in spontaneous behaviour but can easily be demonstrated in the clinical examination. As with all manifestations of apraxia the limbs ipsilateral to the lesion are usually tested to exclude contamination of results by the effects of hemiparesis. Typically the examiner sits on the opposite of the patient and demonstrates the model of the gesture "like a mirror", that is with the right hand if the patient uses the left one. The difficulties and errors of severely apraxic patients are impressive and pose little problems for a reliable diagnosis, but things become more intricate when subtle deviations from normality are considered or when qualitative categorization of errors is attempted (Roy, Black, Winchester, & Barbour, 1996; Roy et al., 2000; Rothi, Raymer, & Heilman, 1997; Haaland & Flaherty, 1984). Hesitation or self-correction which eventually leads to a correct final position is difficult to quantify by mere observation. Kinematic analysis of the imitation of meaningless gestures revealed that such abnormalities are quite common in apraxic patients, but that their severity does not correlate with the severity of apraxia as assessed by spatial errors of the final position (Hermsdörfer et al., 1996).

Apart from meaningless gestures, imitation of meaningful gestures with or without imagined tools or objects (transitive and intransitive gestures) has been tested as well. For detecting dissociations between meaningful and meaningless gestures it is preferable to present them in distinct blocks rather than intermingled, as otherwise subjects may be inclined to make a strategic choice to treat all of them as if they were meaningless (Tessari & Rumiati, 2004; Haaland & Flaherty, 1984).

### 1.1.4 Communicative gestures and pantomimes

Gestures accompanying or replacing speech are a pervasive feature of human face to face communication. A substantial body of research has been devoted to their classification and to elucidation of their communicative and cognitive functions (Kendon, 2004; Ekman & Friesen, 1969; McNeill, 1992) but research on apraxia has traditionally concentrated on only a small sector of their wide variety (1) Emblematic gestures which convey a conventionally defined message like thumb up for approval or the nose thumb for mockery, and (2) pantomimes of object use where use of an object is demonstrated with the empty hand. As a further restriction, diagnosis of apraxia is based on performance of these gestures in response to an explicit command to demonstrate them which deprives them of their genuine communicative role.

For testing emblematic gestures patients need to understand both the general instruction and the verbal designation of the individual gestures. For pantomime of object use the identity of the individual objects can be made clear by showing the object or a picture of it. This may be one reason why clinical diagnosis concentrates on testing the ability to pantomime object use. Nonetheless, aphasic patients with severe comprehension problems may fail to comprehend the instruction at all and in others the nature of errors may raise doubts about full comprehension. The diagnosis is difficult when patients outline the shape at the place where the object would be used (e. g., a pipe before the mouth) or when they use the hand for symbolizing the object (“body part as object”: e. g., opening and closing index and middle finger for scissors). Normal subjects use such strategies too and frequently prefer them to pure pantomime when communicating their needs to someone whose language they do not speak (Duffy & Duffy, 1989; Heilman & Rothi, 1993).

Apraxic errors are obvious when patients perform searching movements for the correct grip or movement or when their pantomime displays some but not all distinctive features of the intended action (e. g., pantomiming drinking from a glass with a narrow grip not accommodated to the width of the pretended glass). In severe cases patients may produce stereotyped circling or swaying movements of the hand which might be interpreted to indicate but not specify movement of the object in peripersonal space. In clinical practice some experience with examination of normal subjects suffices for recognition of significant aberrations, but for research purposes a list of defined features of the pantomime with normative data on their presence in normal subjects’ performance is indispensable (Roy, Black, Blair, & Dimeck, 1998; Goldenberg, Hartmann, & Schlott, 2003).

### 1.1.5 Use of single conventional tools and objects

Misuse of everyday tools and objects is an impressive manifestation of apraxia: Patients try to cut paper with closed scissors, to eat soup with a fork, or to write with the wrong end of the pencil. They bite on the toothbrush instead of brushing, press the knife into the loaf without moving it to and fro, press the hammer upon the nail without hitting, and close the paper punch on top of the sheet without inserting the sheet. As many of these patients have right sided hemiplegia one may be inclined to ascribe their errors to the ineptness of the non-dominant left hand, but it is easy to convince oneself of their pathological nature by observing healthy persons using the tools with the non-dominant hand or doing so oneself. The patients' difficulties are not confined to the testing situation but are observed in their activities of daily living as well (Foundas et al., 1995; Goldenberg & Hagmann, 1998a).

### 1.1.6 Multi-step actions

In daily life one rarely encounters a situation, as in standardized testing for use of single tools and objects, where one is handed a tool and asked to perform its prototypical action on an adequately prepared recipient. Usually the use of the single tool is embedded in a chain of actions involving several tools and objects. Although failure at tests of single tool use predicts difficulties with such naturalistic actions, the reverse is not necessarily the case; more patients fail at naturalistic action than at use of single conventional tools and objects.

Errors in application of single tools and objects which are detectable in explicit testing are likely to show up also in the course of multi-step actions, and the distraction by the additional demands of multi-step actions may bring forward insecurity and failure in use of single tools which have not surfaced in their isolated testing. In addition to these "misuse" errors there are other types of errors specific to multi-step actions. The most important of them are mislocation, omission, toying, and perplexity (for more extensive error classifications see e.g. Rumiati, Zanini, Vorano, & Shallice, 2001; Goldenberg & Hagmann, 1998a; Schwartz, Segal, Veramonti, Ferraro, & Buxbaum, 2002; Mayer, Reed, Schwartz, Montgomery, & Palmer, 1990). Mislocation refers to a correct action performed with the wrong recipient like pouring water into the cup rather than the reservoir of the coffee maker for preparing coffee with a drip coffee maker. Omission of a step is equivalent to the premature performance of another action step which should be initiated only after completion of the omitted one, as for example when turning on the heating of the coffee maker without having inserted water. Toying and perplexity could in principle also affect the isolated examination of single tool use but are much more prevalent in multi-step actions. Toying describes the act of touching or briefly lifting objects not followed by goal-oriented manipulations. Perplexity is diagnosed when patients hesitate unduly before commencing an action or fail to proceed with actions at all.

## 1.2 Anatomical correlates

### 1.2.1 Imitation of gestures

Errors in the imitation of single gestures and sequences was found to be strongly correlated in patients with left sided lesions (De Renzi, Faglioni, Lodesani, & Vecchi, 1983), whereas defective imitation of gesture sequences despite normal imitation of single gestures was demonstrated in patients with right hemisphere lesions, Parkinson's disease or supranuclear palsy (Goldenberg, Wimmer, Auff, & Schnaberth, 1986; Soliveri, Piacentini, & Girotti, 2005; Canavan et al., 1989; Roy, Square-Storer, Hoog, & Adams, 1991). It thus appears that left brain damage affects imitation of single gestures and sequences equally, but that sequences are also vulnerable to lesions elsewhere.

Erroneous reproduction of single gestures has been shown to be body-part specific. Patients with left brain damage have difficulties with the imitation of hand and foot postures while imitation of finger postures is less compromised and can even be completely normal. By contrast, patients with right brain damage have severe difficulties with finger postures and some difficulties with foot postures but imitate hand postures nearly as perfectly as normal controls (Goldenberg, 1996; Goldenberg & Strauss, 2002; Goldenberg, 1996; Goldenberg, 1999). Left hemisphere lesions interfering with imitation need not necessarily be located in regions contributing to language processing: Defective imitation without aphasia has repeatedly been observed in left brain damage (De Renzi, Motti, & Nichelli, 1980; Agostoni, Coletti, Orlando, & Tredici, 1983; Papagno, Della Sala, & Basso, 1993; Goldenberg & Hagmann, 1997). Group studies using CT or MRI consistently found parietal lesions to be the most important, though not the only possible cause of defective imitation (Basso, Luzzatti, & Spinnler, 1980; Haaland, Harrington, & Knight, 2000; De Renzi, Faglioni, Lodesani, & Vecchi, 1983; Goldenberg & Hagmann, 1997; Goldenberg & Karnath, 2006; Cubelli, Marchetti, Boscolo, & Della Sala, 2000) . Lesions are also found in premotor cortex, basal ganglia and white matter, but for subcortical lesions it is questionable whether the lesion itself or associated dysfunction of overlying cortex are causal (Hillis et al., 2002; Weiller et al., 1993).

### 1.2.2 Pantomimes

The association between defective pantomime and left brain damage is tight but not absolute. In systematic group studies about one third of patients with right brain damage are rated lower on behavioural tests than controls, but their scores are very close to the control range, whereas deficiencies of patients with left brain damage and aphasia are distinctly more severe (Cubelli, Marchetti, Boscolo, & Della Sala, 2000; Barbieri & De Renzi, 1988; Roy, Black, Barbour, Mcguiness, & Kalbfleisch, 1998; Roy et al., 2000; Goldenberg, 2003b). A lesion study in a larger sample of patients with left-sided lesions indicated that pantomime deficits are more commonly related to lesions in the inferior-frontal cortex than in other parts of the brain (Goldenberg, Hermsdörfer, Glindemann, Rorden, & Karnath, 2007; Goldenberg & Karnath, 2006). The preservation of pantomime in patients with pure apraxia on imitation from parietal lobe damage supports the implication that parietal lobe damage does not have the same importance for pantomime as for imitation (Goldenberg & Hagmann, 1997; Mehler, 1987).

### 1.2.3 Tool Use

Misuse of everyday tools and objects can be a symptom of dementia caused, for example, by degenerative disease or anoxic brain damage. If caused by unilateral lesions they are left-sided, large, and associated with severe aphasia (De Renzi, Pieczuro, & Vignolo, 1968; Goldenberg & Hagmann, 1998b). Typically inferior and medial regions of the frontal lobe as well as the parietal lobe are included (Goldenberg & Spatt, 2009). Behavioural investigations of single components of tool and object use (see below) point to differential involvement of parietal and temporal regions within the left hemisphere. The ability to infer possible functions from structural properties of objects depends on parietal lobe whereas retrieval of semantic knowledge specifying the purpose of a tool and the typical recipients of its action is bound to temporal lobe integrity (Hodges, Spatt, & Patterson, 1999; Hodges, Bozeat, Lambon Ralph, Patterson, & Spatt, 2000; Spatt, Bak, Bozeat, Patterson, & Hodges, 2002) .

### 1.2.4 Multi-step action

In contrast to the exclusive association of defective use of single familiar tools with left brain damage multi-step actions are affected also by lesions in the right hemisphere (Schwartz et al., 1998a) (Schwartz et al., 1999a) (Goldenberg, Hartmann-Schmid, Sürer, Daumüller, & Hermsdörfer, 2007; Buxbaum, 1998; Hartmann, Goldenberg, Daumüller, & Hermsdörfer, 2005; Humphreys & Forde, 1998) .

### 1.2.5 Callosal apraxia

Liepmann's first patient, the “imperial counselor”, displayed apraxia of only one hand (Liepmann, 1900). Autopsy revealed, among other lesions, a partial destruction of the corpus callosum and Liepmann contended that the subsequent functional division of the hemispheres explained the unilateral of apraxia. The conclusion was that callosal disconnection had deprived the right hemisphere of the left hemisphere's contribution to motor control. Despite some discussion, numerous reports of patients with natural lesions of the corpus callosum have confirmed the reality of left hand apraxia for imitation of gestures, performance of communicative gestures on command and sometimes also object use (Goldenberg, Laimgruber, & Hermsdörfer, 2001; Marangolo, De Renzi, Dipace, Ciurli, & Castriota-Skandenberg, 1998; Tanaka, Yoshida, Kawahata, Hashimoto, & Obayashi, 1996; Graff-Radford, Welsh, & Godersky, 1987; Kazui & Sawada, 1993; Tanaka, Iwasa, & Obayashi, 1990).

## 1.3 Theoretical accounts

### 1.3.1 Imitation of gestures

Rothi and co-workers proposed a cognitive model of apraxia which can account for apraxia on imitation (Rothi, Ochipa, & Heilman, 1991; Rothi & Heilman, 1997a; Rothi & Heilman, 1997b). They distinguished two routes from vision to replication of the demonstrated gesture (see Figure 1). A "direct" route from vision to motor control enables replication of the external shape of the gesture. This route can accommodate both meaningful and meaningless gestures. The "indirect" route is confined to familiar meaningful gestures. Their imitation can be achieved by first recognizing the gesture and then producing a corresponding gesture out of the repertoire of familiar gestures (Tessari & Rumiati, 2004; Goldenberg & Hagmann, 1997; Rothi, Ochipa, & Heilman, 1991; Cubelli, Marchetti, Boscolo, & Della Sala, 2000).

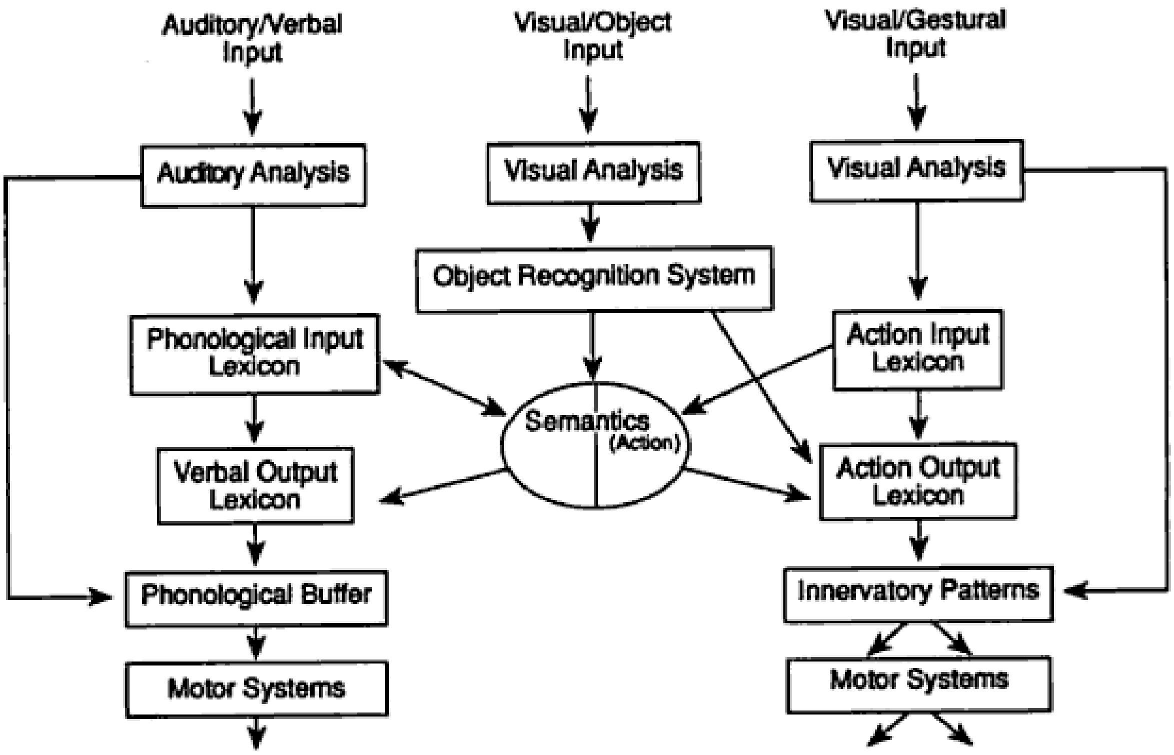


**Figure 1 - Depiction of the two-route model of action selection (based on Rothi et al. 1997).**

The selective interruption of the direct route gives rise to visuo-imitative apraxia where disturbed imitation of meaningless gestures contrasts with perfect performance of meaningful gestures on command or imitation. There is, however, evidence that the "direct" route involves intermediate steps of cognitive processing. Patients who commit errors when imitating meaningless gestures commit errors also when asked to replicate these gestures on a manikin or to match photographs of meaningless gestures demonstrated by different persons and seen under different angles of view (Goldenberg, 1995; Goldenberg, 1999). It has been suggested (Goldenberg & Strauss, 2002; Goldenberg, 1995) that the crucial cognitive step interpolated between perception and replication of meaningless gestures is a coding of the demonstrated gesture with reference to classification of body parts and knowledge of the boundaries defining them. According to this proposal body part coding is a second crucial difficulty in the imitation of novel gestures concerning their perceptual analysis.

### 1.3.2 Pantomimes

Two hypotheses have been proposed for the basic deficit underlying defective pantomime of object use in patients with left brain damage and aphasia. One sees defective pantomime as a manifestation of a general inability to create and use communicative signs which is heightened by the request to produce them outside their natural context (Duffy, Watt, & Duffy, 1994; BAY, 1962). Pantomime of object use is particularly challenging because the gestures are not conventionally used by the patient. In an alternative view the particular difficulty in pantomiming object use originates from the need to perform the motor actions of object use without support from visual and tactile feedback from object properties (De Renzi, Faglioni, & Sorgato, 1982; Bartolo, Cubelli, Della Sala, & Drei, 2003; Liepmann, 1908; BAY, 1962). Indeed most patients who fail at pantomime of object use improve dramatically when allowed to demonstrate use with the object in the hand (De Renzi, Faglioni, & Sorgato, 1982; Goldenberg & Hagmann, 1998a). However, failure of pantomime in combination with intact use of real objects is also compatible with a deficit to process abstract signs and symbols, because real object use does not demand creation of a symbolic representation of the object and its use. Support for this interpretation comes from studies in normal subjects demonstrating that their pantomimes of grasping do not replicate the complete kinematics of real grasping but retain features necessary for depicting the object and the action (Goodale, Jakobson, & Keillor, 1994; Laimgruber, Goldenberg, & Hermsdörfer, 2005).

### 1.3.3 Use of single conventional tools and objects

A distinction has been made between knowledge of a tool's purpose and of its manipulation. Indeed typical errors of apraxic patients, like pressing the knife on the loaf without the sawing movement, provide the impression that patients still know the goal of the action (dividing the loaf) but not how to reach it. It has been postulated that both kinds of knowledge constitute distinct compartments of semantic memory and can be lost independently from each other (Boronat et al., 2005; Buxbaum & Saffran, 2002). Another hypothesis proposes that a second, non-semantic, route enables inference of possible functions from structural properties of objects. Whereas semantic functional knowledge is basically restricted to the prototypical use of familiar tools, the non-semantic route permits detection of functions of novel tools as well as of non-prototypical applications of familiar tools (Goldenberg & Hagmann, 1998a; Carmo & Rumiati, 2009; Hodges, Spatt, & Patterson, 1999; Hodges, Bozeat, Lambon Ralph, Patterson, & Spatt, 2000; Rumiati & Humphreys, 1998). Support for the existence of such a division comes from double dissociations between patients who have independently lost one or the other capacity ascribed to these routes to action. There are patients with pervasive deterioration of semantic memory who have lost any knowledge about familiar tools and objects but are able to manipulate them in a sensible way which, however, may not serve the usual goal of that tool. For example, they may find out that a nail-clipper can be used for cutting but not that it is used for cutting nails (Hodges, Bozeat, Lambon Ralph, Patterson, & Spatt, 2000; Sirigu, Duhamel, & Poncet, 1991). Conversely, there are patients who have retained knowledge about the prototypical use of familiar objects but neither can detect the function of novel tools nor ways for achieving a given purpose (e. g. fixing a screw) in the absence of the usual tool by non-prototypical application of other familiar tools or objects (Hodges, Spatt, & Patterson, 1999; Spatt, Bak, Bozeat, Patterson, & Hodges, 2002; Goldenberg & Hagmann, 1998a; Heilman, Maher, Greenwald, Rothi, & Maher, 1997; Osiurak, Jarry, & Le Gall, 2011).

The second route can at least partially compensate loss of semantic knowledge of an objects appropriate use. Consequently, failure to use familiar conventional tools and objects should become manifest only in patients in whom both routes to action are compromised by brain damage, and this seems indeed to be the case in patients with apraxia from left brain damage (Goldenberg & Hagmann, 1998a).

### 1.3.4 Multi step actions

There are two ways to explain the common disruption of naturalistic actions by lesions in either hemisphere. It may be due to depletion of attentional resources which are not bound to any specific location but depend on the integrity of the whole brain (Schwartz et al., 1999a). Alternatively, the errors may have different causes in patients with damage at different locations, but these differences do not manifest as differences in the error profile because functional interactions between the multiple tools and objects constrain the range of possible errors and render observation of errors opaque as to the causes of failure (Hartmann, Goldenberg, Daumüller, & Hermsdörfer, 2005). Support for the importance of general attentional depletion is provided by the repeatedly observed association between number of errors and severity of hemi-neglect in patients with right brain damage. There is no preponderance of errors in the left side of working space or of objects (Schwartz et al., 1999a; Goldenberg, 2003a; Goldenberg, 2003b) suggesting that both severity of hemi-neglect and errors on multi-step actions are expression of an underlying non-spatial reduction of attentional resources (Husain & Rorden, 2003). Different specific causes of errors in different patient groups is suggested by a strong correlation between errors in making coffee and linguistic abilities in patients with left brain damage and aphasia (Hartmann, Goldenberg, Daumüller, & Hermsdörfer, 2005) whereas patients with right brain damage, whose language is unimpaired, do no better at making coffee than the aphasic patients.

Other approaches to naturalistic multi-step actions interpret task demands and causation of errors in the framework of executive function and the supervisory control of action (Cooper & Shallice, 2000; Rumiati, Zanini, Vorano, & Shallice, 2001; Humphreys & Forde, 1998; Forde, Humphreys, & Remoundou, 2004). Finally, a promising approach is computational modelling of the interactions between the multiple cognitive components contributing to success on such mundane tasks as preparing coffee, tea or orange juice (Cooper & Shallice, 2000; Botvinick & Plaut, 2004; Cooper, Schwartz, Yule, & Shallice, 2005).

### 1.3.5 Ideational and ideo-motor apraxia

The dichotomy between “ideational” or “ideo-motor” apraxia was originally elaborated by Liepmann (Goldenberg, 2003b; Liepmann, 1908). It was based on a distinction between non-localizable “psychic” and localizable sensory and motor function of the cerebral cortex. Liepmann (1908) distinguished the generation of ideas of intended actions as a non-localizable “psychic” function depending on integrity of the whole cortex at an “ideo-motor” level where ideas are transformed into appropriate muscular actions. This level is hypothesized to be intermediate between purely motor and purely “psychic” functions and to depend on integrity of only the left hemisphere. However, as summarized below, a review of criteria proposed by different authors for discriminating ideational from ideo-motor apraxia does not provide much clarity.

Defective imitation of meaningless gestures has been considered as "not really related to the understanding of apraxia" by two influential authors (Geschwind & Damasio, 1985). It has been acknowledged as a core manifestation of ideomotor apraxia by others (De Renzi, Motti, & Nichelli, 1980; Kimura & Archibald, 1974), but this acknowledgement has been challenged by the evidence, reviewed above, that patients fail at imitation because of insufficient perceptual and conceptual processing of demonstrated gestures rather than insufficient motor control. Erroneous production of communicative gestures on command has been said to emanate either from the inability to retrieve the appropriate gesture from semantic memory, which would classify as ideational, or from defective motor execution, which would classify as ideo-motor (Roy & Hall, 1992; Barbieri & De Renzi, 1988; De Renzi, 1990; Heilman & Rothi, 1993) . The ambiguity should be resolved by observation of the types of errors. "Distorted movements" (Poeck, 1982) which "do not concern the general configuration of the gesture" (De Renzi, 1990) were considered indicative of ideo-motor apraxia, but the decision whether or not an error distorts the general configuration or only a detail of a gesture may leave considerable space for divergence of interpretation. Defective use of single tools and objects has been considered as being due to insufficient motor execution and hence ideo-motor apraxia by some authors (Poeck, 1982) and as the hallmark of ideational apraxia by others (De Renzi & Luchelli, 1988). Omissions and confusions in the sequential ordering of multi-step actions were core symptoms of the original description of ideational apraxia (Liepmann, 1908; Lehmkuhl & Poeck, 1981; Poeck, 1982), but have recently been considered as constituting an "action disorganization syndrome" (ADS) distinct from apraxia (Buxbaum, 1998; Humphreys & Forde, 1998). A proposal to call difficulties with single tools and objects "conceptual apraxia" and those with multi-step actions "ideational apraxia" (Heilman & Rothi, 1993; Raymer & Ochipa, 1997) adds to the nomenclatorial confusion without clarifying the nature of their differences.

Given that the theoretical basis is questionable and the mainly clinical application of the distinction between ideational and ideo-motor apraxia, it is proposed to abandon the dichotomy and to replace it by unprejudiced inquiries into the mechanisms and cerebral substrates of each of the domains affected.

## 1.4 Action Disorganisation Syndrome

### 1.4.1 Definition

Action disorganisation syndrome (ADS) is a neuropsychological disorder following brain injury. It was first described by Schwartz and colleagues (Schwartz, Reed, Montgomery, Palmer, & Mayer, 1991). ADS is characterized by a high proportion of cognitive errors when performing everyday tasks, such as making a cup of coffee or dressing, but it is not caused by a motor deficit (Morady & Humphreys, 2009). Patients might perform the action in a wrong sequence (pouring water into the cup without inserting a tea bag) or using inappropriate objects (using a fork for stirring). For example, Schwarz et al. (1991) described a patient (HH) with ADS after bilateral frontal brain injury. HH made several errors when making a cup of instant coffee such as putting butter into the coffee or adding coffee grinds into a bowl of oatmeal. In the tooth brushing task, in contrast, HH repeatedly turned the tap on and off, or wet the toothbrush several times. However, the exact pattern of errors varies from one patient to another, depending on lesion localisation and size. Although ADS is often associated with frontal lesions, it can also ensue after a variety of lesions (e.g. Schwartz, Reed, Montgomery, Palmer, & Mayer, 1991; Schwartz et al., 1995). Taken together, patients with ADS are impaired in their cognitive ability to carry out activities of daily living (ADL), diminishing their independence and making them more dependent on caregivers and healthcare systems.

### 1.4.2 Diagnosis and Action Coding System

Patients' performance on routine, everyday tasks can be assessed by using the Action Coding System (ACS), a standardized measure of type and number of errors, developed by Schwartz et al. (1991). Here, each ADL task such as making a piece of toast was divided into smaller units of action, so called A-1 steps. These basic units of actions are defined as "the smallest component of a behavioural sequence that achieves a concrete, functional result or transformation, describable as the movement of an object from one place to another or as the change in the state of an object" (Schwartz, Reed, Montgomery, Palmer, & Mayer, 1991 p. 384). Individual A-1 steps can be grouped together and form basic subgoals and subroutines (A-2). For example, making a cup of tea consists of several A-2 steps: Heat water, insert a tea bag into the cup, pour hot water onto the teabag, and add milk and/or sugar. The A-2 step 'add milk' would involve the following A-1 steps 'lift the milk bottle, open the lid, move the milk bottle to the cup, pour milk into the cup'. It is important to note that these A-1 steps and A-2 steps can differ between subjects depending on whether or not they like to have milk or sugar in their tea. Taken together, the ACS enables us to divide complex tasks into basic units of action in order to assess whether and which steps could be accomplished by the patient. This allows distinguishing between errors at different levels. Moreover, the proportion of independent A-1 steps (e.g., 'lift milk bottle' or 'move milk bottle') can be used as an indicator for the coherence of task performance (Schwartz, Reed, Montgomery, Palmer, & Mayer, 1991).

Another way of evaluating patients' performance on routine tasks has been suggested by Humphreys and Forde (1998). They asked 45 normal participants to describe the necessary steps to accomplish certain tasks (making a cup of tea, wrapping a gift, posting a letter, making a toast, making a cheese sandwich, preparing cereal, and painting a block of wood). Unsurprisingly, there was a high similarity between the basic components and their temporal sequence between the subjects. These normative sequences (for each task) generated by normal participants can be used to assess patients' task performance. In Figure 2, the normative sequence for the tea making task is illustrated. Additionally, patients' performance can be also evaluated in relation to the performance of control participants (Schwartz et al., 1998a).

**Task: Make a Cup of Tea with Sugar**

| Normal Basic Level Actions: | Actions by Patient: | Error Type: |
|---|---|---|
| Put teabag in teapot | | Omission |
| Pour water into teapot | Pour water into teapot | |
| Put milk in cup | Pour milk into teapot | object substitution |
| Pour tea in cup | Stirs teapot | object substitution |
| Put sugar in tea | Pours teapot-> cup | omission |
| Stir tea | Stirs tea in cup | |

**Figure 2 - Example of how task performance of an ADS patient can be assessed relative to the basic steps for the task generated by normal participants. (From Humphreys & Forde, 1998).**

### 1.4.3 Error types and their frequency

Schwartz et al. (1991) distinguished between the six error types (Table 1): (1) place substitutions (moving the object to the wrong destination, e.g. putting coffee into oatmeal), (2) object substitution (misuse of objects, e.g. adding orange juice to the coffee), (3) anticipation (performing an action in the wrong sequence, e.g., drinking tea without adding a tea bag), (4) omissions (missing one step before carrying out another step, e.g., putting spread onto the toast without toasting it), (5) tool substitutions (using the wrong tool, e.g., stirring tea with a fork), and (6) quality errors (the action was carried out but not in the appropriate way, e.g., the packet of sugar was not completely opened). According to Schwartz et al. (1998a), these error types can be broadly divided into two categories: *Errors of omission* (the failure to execute critical actions or sequence of actions) and *errors of commission* (performing an action in an incorrect or inappropriate way). The later one includes sequence errors (performing an action in the wrong order), additions (adding an extra component action), semantic errors (using a semantically related object instead of the correct one), perseverations (repeating an action or action sequence), and quality or spatial errors (using an inappropriate amount of ingredients or failing to use tools).

**Table 1 - Summary of error types based on studies by Buxbaum, Schwartz and Montgomery (1998) and Schwartz and colleagues (1999a; 1998a). Note: (From Cooper, Schwartz, Yule, & Shallice, 2005)**

| *Error Type* | *Examples* |
|---|---|
| Step omission | Failure to pack cookies, sandwich or drink into the lunch box<br>Failure to include filling when making the sandwich |
| Sequence: Anticipation/Omission | Packing the sandwich without first wrapping it in foil<br>Attempting to pour from the juice jar without first opening it |
| Sequence: Reversal | Packing the cookies or sandwich and then wrapping them<br>Placing cookies or sandwich on foil before tearing foil from roll |
| Sequence: Perseveration | Taking more than two slices of bread for the sandwich<br>Wrapping the cookies or sandwich more than once |
| Object substitution | Packing the lunch items into the schoolbag instead of the lunch box<br>Using apple sauce instead of mustard on the sandwich |
| Action addition | Eating the sandwich or the cookies<br>Packing inappropriate items (e.g., the mustard jar) into the lunch box |

Several case studies with ADS patients have used the ACS to assess patients' performance (Morady & Humphreys, 2009; Schwartz, 1995; Schwartz et al., 1995; Schwartz et al., 1998a; Forde, Humphreys, & Remoundou, 2004; Schwartz, Reed, Montgomery, Palmer, & Mayer, 1991; Morady & Humphreys, 2011; Forde & Humphreys, 2002; Forde & Humphreys, 2000; Humphreys & Forde, 1998). It has been shown that some error types are more frequent than others. For example, Schwarz et al. (1998a) found that patients with closed brain injury (CHI) omitted more steps (40%) and made more sequence errors (20%) when performing everyday tasks. A similar result was obtained for patients with right hemisphere stroke (RCVA; Schwartz et al., 1999a), patients with left hemisphere stroke (LCVA; Buxbaum, Schwartz, & Montgomery, 1998; see Figure 3), and for two ADS patients (Humphreys & Forde, 1998). As Figure 3 shows, step omissions were the most frequent error, followed by sequence and addition errors. Additionally, these studies have revealed that clinical severity highly correlates with omission errors, indicating that patients with high error rates made more omission errors while commission errors are more frequent in patients with low error rates (Schwartz et al., 1998a, 1999). Based on these results, it seems that omission errors are a good indicator for disorganized actions.

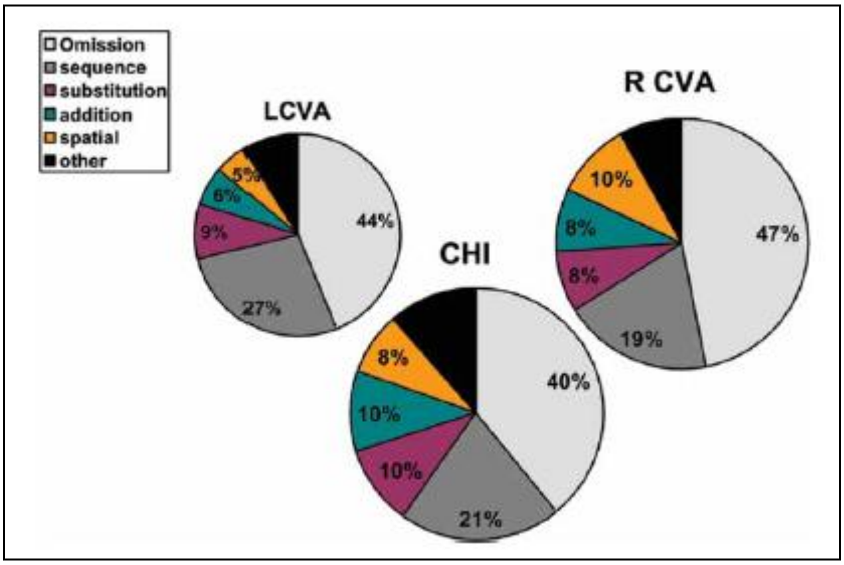


**Figure 3 - The distribution of errors by error type for patients with closed brain injury (CHI), right hemisphere stroke (RCVA) and left hemisphere stroke (LCVA). (From Schwartz, 2006).**

### 1.4.4 Mechanisms underlying ADS

It is of particular interest to elucidate the mechanisms underlying ADS in order to define and provide a persistent and continuous rehabilitation. To date, the mechanisms of ADS are still unclear. An overview of possible accounts of ADS will be given in the next section.

### 1.4.5 Norman-Shallice theory of attention and action

One of the first explanations of how disorganisation is caused is based on the Norman-Shallice theory of attention and action (Norman & Shallice, 1986). According to this model, ADS might result from a failure of the contention scheduling system (CSS) due to a damaged supervisory attention system (SAS) or malfunction within the CSS itself. Briefly, the CSS is thought to be responsible for controlling routine tasks (e.g., toothbrushing or making a cup of coffee, whereas non-routine tasks (e.g., making a cup of coffee and doing a mental calculation simultaneously) and error monitoring may require the involvement of the SAS which is located in the frontal lobes (Shallice, 1988). This implies that routine activities may require fewer demands on SAS than non-routine activities. This model will be discussed in more detail in chapter 2.3.

Contrary to this SAS impairment assumption, Humphreys and Forde (1998) showed that frontal lobe damage causing executive dysfunction cannot account for patients' impairments. Although all of their three patients had frontal lobe damage (and their performance on executive task was equally impaired) only two of them (FK, HG) fulfilled the criteria of ADS. Both ADS patients made significantly more errors on routine tasks compared to the control patient with 'only' executive dysfunction, indicating that frontal lobe damage does not necessarily lead to disorganised behaviour.

Additional support against the impaired SAS hypothesis is given by Schwartz and colleagues. They studied everyday action performance in patients with closed head injury (N = 30, Schwartz et al., 1998a), left hemisphere stroke (N=16, Buxbaum, Schwartz, & Montgomery, 1998), and right hemisphere stroke (N = 30, Schwartz et al., 1999a). In these studies patients carried out three naturalistic tasks (wrapping a gift, making toast, packing a lunchbox). Surprisingly, there was a remarkable similarity with regard to the proportion of error types not only between the patient groups (cf. Figure 1) but also between patients and controls (Schwartz et al., 1998a). The fact that patients made more errors than controls (particularly omission errors), even on simple tasks, did not support the SAS account. Moreover, although patients' error rate increased with more task demands (e.g., presence of distractors) this held only for omission errors (the most common error produced by the patients). Given that patients with different aetiologies perform worse even on routine, multi-step tasks did not support the SAS account. Taken together, there is empirical evidence that an impaired SAS is not sufficient to cause and explain disorganised behaviour.

### 1.4.6 <u>Deficits in inhibition of action</u>

Humphreys and Forde (1998) proposed that ADS is due to an impaired ability to inhibit previously executed actions which is known as perseveration. Although both ADS patients (FK, HG) performed worse on many everyday tasks and made similar errors, they differed with respect to their perseveration errors. HG made more 'continuous' perseverations, whereas FK made more 'recurrent' perseverations. For example, when wrapping a gift HG tended to continue cutting wrapping paper. FK, in contrast, would pour again milk into the tea although he already poured milk into the tea some time before. Based on these results, they suggested that 'continuous' and 'recurrent' perseverations are caused by different mechanisms. Humphreys and Forde proposed that 'continuous' perseveration may be impeded by an error-monitoring process or by the process of 'rebound inhibition' immediately after selection, while 'recurrent' perseveration may be impeded by an 'activation gradient' which can be understood as a form of memory which comprises information about the component actions as well as the temporal order of these actions for a particular task. According to this idea, an action will be inhibited immediately after selection by rebound inhibition processes and may reset to baseline activation, whereas the activation gradient enables that the next action will be the most highly activated representation in this sequence (see also Humphreys, Forde, & Riddoch, 2001). Using this framework, it seems that HG has a deficit in initiating the process of 'rebound inhibition', resulting that the same action will be repeated immediately. FK, in contrast, may have a damaged 'activation gradient; which might not activate the next action strongly enough, leading to a competition between earlier and later action sequences. As a result of this competition, a previously executed action in the sequence might be repeated after a while.

### 1.4.7 <u>Resource deficits</u>

Schwartz et al. (1995; 1998a) assumed that limited-capacity resources rather than a specific lesion can lead to ADS. This 'non-specific cognitive resource' hypothesis predicts that the higher the task requirements the higher the error rate, indicating that patients have more difficulties in maintaining all necessary information to accomplish the task successfully. In particular, it has been suggested that there will be a predominance of omission errors, particularly with higher task demands. This account has been supported by their control subjects who performed worse on everyday tasks when distracters were presented (cf. Reason, 1984; Norman, 1981, for action errors in normal participants).

However, the results by Forde and Humphreys (2002) did not support the prediction from this hypothesis. Although their patient (FK) omitted more steps when performing everyday tasks (e.g., making a cup of tea), there was a difference when FK performed these task under increased or decreased task demands. For example, under decreased task demands (e.g., when a photograph depicted the goal) his error pattern was the same (i.e., the majority of errors were step omissions). In contrast, he made more 'recurrent' perseverations (38%) than omissions (23%) under increased task demands (e.g., when he was interrupted in performing the task by having short breaks at 1-2 minutes intervals). In addition, when FK had to perform a secondary task during the break intervals 'recurrent' perseverations were the most prominent error type (39%). This indicates that FK had problems in maintaining which actions steps have been already executed. Notable, there was also a difference in FK's error profile when performing the different activities. He made fewer omissions but more perseverations during the tea making and letter writing task, whereas the opposite pattern has been observed during the sandwich and gift task.

### 1.4.8 <u>Deficits in error monitoring</u>

Morady and Humphreys (2009) revealed that under dual-task load conditions the number of errors increased in normal participants as well as in a patient (FK) with clinically signs of ADS but their error profile was different. Whereas FK performance was strongly affected by related distractors (relative to unrelated distractors) and led to more omission errors, normal participants made more sequence errors and did less self-correcting actions when performing a secondary task. Based on these results, Morady and Humphreys (2009) argued that FK's problems in performing multi-step tasks may arise due to specific deficits which increase during task load rather than task demands or executive recourses per se.

# 2. REVIEW OF THE LITERATURE (INCLUDING TESTING METHODS)

CogWatch primarily addresses problems of brain damaged patients during the actually use of tools and objects. This review will therefore focus on the interaction with tools and objects in simple as well as more complex situations. Other prominent manifestations of apraxia such as errors during imitation and pantomime have been described in the Introduction and will only be addressed if relevant.

## 2.1 Tool use

### 2.1.1 Deficits during use of single tools

It has been pointed out in the Introduction that errors during tool use are one of the core manifestations of apraxia although frequency and severity of errors is usually ameliorated compared to pantomiming the corresponding tool use action. For the latter reason many clinical test have concentrated on the more sensitive pantomime test. However, predictability of individual performance from pantomime tests to actual tool use has been shown to be quite limited. Consequently testing the use of actual tools with real target objects seems essential to predict the patient's ability in interacting with tool and objects of everyday living.
Table 2 summarizes clinical studies testing the use of actual tools. In particular, studies that tested the use of single tools and used scoring systems are displayed.

**Table 2 - Summary of reports on performance deficits during the use of actual tools following brain damage.**

| Source | Items | Main result | Scoring | Other Tasks |
|---|---|---|---|---|
| (Liepmann, 1908) | comb, brush, hammer, cigar, pour water, knot, music instrument etc.. | errors in 25% of "dyspraxics" (N=42) | right/wrong | Imitation, emblematic gestures, pantomime |
| (De Renzi & Luchelli, 1988) | "objects of common use" | "all of them (11 LBDs) made errors" | major/minor/no error | Imitation, pantomime, multiple-objects |
| (McDonald, Tate, & Rigby, 1994) | comb, toothbrush, cup, spoon, key, fan, scissors, pen hammer, pistol, screwdriver, coin | 17 LBD: not differentiated from other task modes | right/wrong | pantomime (verbal command & imitation) |

| Source | Items | Main result | Scoring | Other Tasks |
|---|---|---|---|---|
| (Belanger, Duffy, & Coelho, 1996) | stamp, hammer, fork, razor, scissors, spoon, toothpaste, soap, key, matches, screwdriver, pencil, knife, saltshaker, hand saw | 25 LBD vs. CTR: $p = .002$ | correct<br>distorted<br>delayed<br>incomplete<br>self-corrected<br>inaccurate<br>perseveration<br>unintelligible<br>needs repetitions | pantomime (verbal command, tactile, imitation),<br>imitation |
| (Goldenberg & Hagmann, 1998b) | fan, binoculars, comb, scissors, pencil, gum, hammer, electric bulb, key, bottle | 42 LBD vs. CTR: $p < 0.05$ | major/minor/no error | pantomime, novel tools |
| (Buxbaum, Giovannetti, & Libon, 2000) | 18 common objects: hammer etc. | singe case: errors less during use | grasp<br>trajectory<br>amplitude<br>timing | pantomime (command, imitation), emblems, other tests |
| (Westwood et al., 2001) | hammer, saw, pick up ball, spectacles, key, comb, spoon, toothbrush | object use deficit: 37 LBD 43 % (panto ok) + 30% (panto -), 50 RBD 18 % + 9 % | performance accuracy from composite scores | pantomime |
| (Goldenberg, Hentze, & Hermsdörfer, 2004) | glass, apple, electric bulb, key, comb, screwdriver, hammer, saw, flat iron, lemon squeezer, pencil, spoon | 10 LBD: use of actual tools more errors than othe conditions ( $p < 0.01$) | presence of feature for grasp and movement | pantomime, neural handle |
| (Goldenberg & Spatt, 2009) | hammer, scissors, screwdriver, key, spanner | 17 of 38 LBD patients scored below CTR | selection of correct recipient, correct application | functional associations, novel tools |
| (Randerath, Spijkers, Goldenberg, Li, & Hermsdörfer, 2011) | hammer, laddle | 25 LBD vs. CTR; $p < 0.05$ in all cond. except scooping/ actual use | presence of features: grasp, movement execution, direction, space | pantomime, demonstration |

## Movement execution during use of tools

The studies summarized in the preceding section used scoring methods to measure the quality of gesture execution. The judgment included global aspects of success or involved various error types. The temporal and spatial characteristics of the movements are sub-aspects in some of the scoring methods but the assessment is very coarse. A number of studies concentrated however on these performance aspects. These approaches registered movements in three-dimensional space using adequate technical methods and analysed kinematics.

**Table 3 - Summary of reports analysing three-dimensional movement kinematics during tool-use in patients with brain damage**

| Source | Tasks | Main result | Other execution modes |
|---|---|---|---|
| (Clark et al., 1994) | slicing bread | 3 LBD: imprecise plane of motion & trajectory shape, impaired coupling between hand speed & trajectory shape | Pantomime only, tool only, target object |
| (Poizner et al., 1995) | slicing bread | 3 LBD: impaired joint coordination | pantomime only, tool only, target object |
| (Laimgruber, Goldenberg, & Hermsdörfer, 2005) | grasping a glass | 19 LBD, 10 RBD: prolonged adjustment phase; RBD: slowed velocity | pantomime |
| (Hermsdörfer, Hentze, & Goldenberg, 2006) | sawing | 9 LBD: velocity deficits | pantomime, neutral handle |
| (Hermsdörfer, Li, Randerath, Roby-Brami, & Goldenberg, 2012) | hammering | 23 LBD: prolonged RT, slowed velocity, 10 RBD: prolonged RT | pantomime only, tool |
| (Hermsdörfer, Li, Randerath, Goldenberg, & Johansson, 2012) | scooping | 23 LBD: reduced amplitude, reduced hand roll 9 RBD: no deficits | pantomime only, tool |

### 2.1.2 Execution of goal directed movements

While studies comprising movement recordings during tool use are relatively rare in patients with left or right brain damage, a substantial number of studies have investigated the kinematics of more basic goal-directed movement such as pointing and aiming to targets or grasping neutral objects. As outlined below, these studies have generally revealed specific deficits in patients with left versus right brain damage, with deficits of more dynamic aspects of movement following damage to the motor dominant left hemisphere and deficits of movement initiation and movement accuracy following damage to the right hemisphere .

**Table 4 - Summary of studies of performance deficits during goal-directed movements with the ipsilesional hand in brain damaged patients**

| Source | Tasks | Main result |
|---|---|---|
| (Fisk & Goodale, 1988) | pointing | LBD: MT deficits<br>RBD: RT deficit |
| (Haaland & Harrington, 1994) | repetitive pointing | LBD: MT deficits during low accuracy movements (open loop)<br>RBD: no deficits |
| (Winstein & Pohl, 1995) | repetitive pointing (Fitts Law) | LBD: MT prolonged, reversal phase prolonged<br>RBD: MT prolonged, adjustment prolonged |
| (Hermsdörfer, Ullrich, Marquardt, Goldenberg, & Mai, 1999) | grasping | LBD: acceleration deficits<br>RBD: adjustment deficits |
| (Hermsdörfer, Laimgruber, Kerkhoff, Mai, & Goldenberg, 1999) | grasping & placing | LBD: slowed movement, awkward hand rotation<br>RBD: prolonged RT, slowed movement, hand placement errors |
| (Hermsdörfer, Blankenfeld, & Goldenberg, 2003) | pointing to 3d-targets | LBD: kinematic deficits during more complex pointing<br>RBD = CTR |
| (Schaefer, Haaland, & Sainburg, 2007) | shoulder/elbow aiming | LBD: reduced acceleration amplitude<br>RBD: reduced acceleration duration |
| (Tretriluxana, Gordon, Fisher, & Winstein, 2009) | grasping | LBD: deficient scaling of grasp preshaping<br>RBD: weak transport-grasp coordination, prolonged MT |
| (Schaefer, Haaland, & Sainburg, 2009b) | shoulder/elbow aiming | LBD: impaired multi-joint coordination<br>RBD: decreased final accuracy |
| (Schaefer, Haaland, & Sainburg, 2009a) | visuomotor adaptation | LBD: initial direction adaptation impaired<br>RBD: final adjustment impaired |
| (Haaland et al., 2009) | elbow aiming movements | LBD + paresis: reduced amplitude modulation |
| (Mutha, Sainburg, & Haaland, 2010) | visuomotor adaptation | LBD + apraxia >> impaired |
| (Mutha, Sainburg, & Haaland, 2011) | visuomotor adaptation | LBD parietal damage >> impaired |

Interest in motor deficits apart from the typical contralateral paresis and sensory loss following stroke extended also to other motor abilities such as strength, tracking tasks, or artificial complex movement sequences. For strength of the non-paretic hand findings are ambiguous. If present, moderate to mild strength deficits seem to vary with the joints involved in the force production (Colebatch & Gandevia, 1989; Jones, Donaldson, & Parkin, 1989). Tracking and other complex task typically yield mild to moderate deficit on the non-paretic hand of stroke patients (Haaland & Harrington, 1989; Jones, Donaldson, & Parkin, 1989; Yelnik et al., 1996). Deficit in the global performance measure typically do not differ between LBD and RBD patients. Notably, learned artificial movement sequences seem to be particularly impaired following damage to the dominant left brain (Harrington & Haaland, 1992; Kimura, 1977).

### 2.1.3 Multi Step Actions – Everyday tasks

Over the last 10 years, a number of studies on patients with different aetiologies as well as on healthy participants have been carried out in order to gain new insights into the nature of ADS – a neuropsychological disorder which is characterised by a high proportion of cognitive errors when performing multi-step everyday tasks (e.g., making a cup of tea) (Morady & Humphreys, 2009). The most relevant studies which have investigated patients' performance on multi-step everyday tasks and their main results are listed in Table 5. The main conclusions from these studies can be summarized as follows: (i) Given that patients with closed head injury, with left hemisphere stroke as well as with right hemisphere stroke made many errors when carrying out familiar everyday activities, it can be concluded that ADS occurs after a variety of lesions rather than due to lesions of a single cortical area. (ii) Unexpectedly, the error pattern between the different patient groups was quite similar: step omission (missing one step before carrying out another step) was the most frequent error, followed by sequence errors (performing an action in the wrong order) and addition errors (adding an extra component action). This indicates that omission errors are the most characteristic feature of ADS. (iii) However, the exact pattern of errors varies from one patient to another, indicating that more than one mechanism is impaired. For example, Humphreys and Forde (1998) reported that two ADS patients (FK, HG) differed with respect to their perseveration errors when performing routine, everyday tasks. Taken together, ADS patients perform worse on everyday activities and this has dramatic effects on their daily life and independence.

**Table 5 - Summary of reports on performance deficits in patients with ADS**

| Source | Aim | Number of patients | Task | Main results |
|---|---|---|---|---|
| Bickerton, Humphreys, & Riddoch (2006b) | Verbal rehabilitation training | ADS patient (N=1) | Making a cup of tea, making a toast | Pre-training: achieved 58% of the maximum score possible, self-corrections on 1/9 trials; post-training: achieved 63.5% of the maximum score possible, self-corrections on 4/9 trials, no generalisation to unlearned tasks (e.g., making coffee and toast together). |
| Bickerton, Humphreys, & Riddoch (2007) | Effect of object familiarity in everyday tasks | ADS patient (N=1); patients with brain lesions (N=4); age- and sex matched controls (N=5) | Making a cup of tea, wrapping a gift, write and prepare a letter for posting, open and reply to a letter, making a toast, making a sandwich and pack a lunchbox, making a cup of coffee, putting an article from a magazine into a file | ADS patient made more omission steps with unfamiliar (7 errors) than familiar objects (4 errors) compared to controls (2 and 0.5 errors, respectively), total error rate increased with unfamiliar objects (M= 18) compared to familiar objects (M=11). |
| Bickerton, Riddoch, Samson, Balani, Mistry, Humphreys (2012) | Multiple-Step Object-Use Test (MOT) for functional evaluation | Left and right hemisphere stroke (N=635) | Mounting a torch and switching on light | No differences between LBD and RBD in MOT score, no correlation between MOT and SOT (Single Object-use Test), low but consistent correlation between MOT and Barthel Index (r=0.29) and Nottingham Extended ADL scale (r=0.32) |

| Source | Aim | Number of patients | Task | Main results |
|---|---|---|---|---|
| Buxbaum, Schwartz, & Montgomery (1998) | Naturalistic action performance of patients with left hemisphere stroke | Patients with left hemisphere stroke (N=16) | Wrapping a gift, making toast, packing a lunchbox | Omissions (44%), sequence errors (27%). |
| Forde & Humphreys (2000) | Role of semantic knowledge & working memory | ADS patient (N=1) | Making a cup of tea, wrapping a gift, posting a letter, making a toast, making a sandwich, preparing cereal, tooth brushing, shaving, painting wood | Omissions (36%), perserverations (31%), semantic errors (11%), sequence errors (10%); related distractors: same pattern of errors; no improvement with written commands, better performance with sequential commands, copying a task and stepped-copy task. |
| Forde & Humphreys (2002) | Factors that modulate performance | ADS patient (N=1) | Making a cup of tea, wrapping a gift, posting a letter, making a toast, making a sandwich, preparing cereal, painting wood | Omissions (39%), perserverations (18%), additions (16%), sequence errors (15%); related distractors: same pattern of errors; no improvement (1) with photographs depicting the goal, (2) written commands, (3) sequential commands, and (4) stepped-copy task; better performance when copying a task; interruptions caused more perserverations (38%) than omissions (23%); interruptions with intervening task increased error rate (perserverations 39%); tea making and letter writing task caused less omissions but more perserverations than during sandwich and gift task. |

| Source | Aim | Number of patients | Task | Main results |
|---|---|---|---|---|
| Giovannetti, Schwartz, & Buxbaum (2007) | Simulating ADS and routinization | Healthy participants (N=17) | Making two cups of coffee | Error rates and completion times decreased with late practice (M=10.5, M=74 sec, respectively) compared to early practice (M=17.7, M=100sec, respectively); proportion of anticipation sequence errors and of detected errors increased with late practice (M=.89 and M=.93, respectively) compared to early practice (M=.75, M=.79, respectively); dual-task condition (coffee making +additional task) affected speed and accuracy but no increase in omissions or undetected errors. |
| Humphreys & Forde (1998) | Naturalistic action performance of ADS patients | ADS patient (N=2) | Making a cup of tea, wrapping a gift, posting a letter, making a toast, making a sandwich, preparing cereal, tooth brushing, shaving, painting wood | Omissions (24%), sequence errors (40%); patients better with shorter than with longer tasks; HG equally same number of errors in the first and second halves of the tasks, FK better in the first half of the task; HG made 'continuous' perserverations, FK made 'recurrent' perserverations. |
| Morady & Humphreys (2009) | Effect of distractors (related vs. unrelated) | ADS patient (N=1) | Making a cup of tea, making a sandwich, wrap a gift, write a card and prepare it for the post | Absence of distractors: omissions (33 %), sequence (11%), toying (7%); related distractors: omissions (20 %), sequence (4 %), toying (5%); unrelated distractors: omissions (26 %), sequence (1 %), toying ( 5%). |

| Source | Aim | Number of patients | Task | Main results |
|---|---|---|---|---|
| Morady & Humphreys (2011) | Effect of multiple task demands | ADS patient (N=2) | Making a cup of tea, making a sandwich, wrap a gift, prepare a card for the post | Omissions (FK [n=12]; BL [n =7]), sequence errors (FK [n=5; BL [n=1]); quality/spatial errors (FK [n=1]; BL [n=5]; omission and sequence errors decreased when (1) patients had to instruct the experimenter, (2) verbal cues, (3) verbal cue with direct feedback (BL > FK); no omission or sequence errors with single actions with verbal cue but other errors still occurred. |
| Schwartz, Reed, Montgomery, Palmer, & Mayer (1991) | Naturalistic action performance of an ADS patient | ADS patient (N=1) | Making a cup of instant coffee, toothbrushing | More errors during coffee making task (3.43 errors/session) than during tooth brushing (3.0 errors/session); Making coffee: place substitutions (n=42), subject substitutions (n=15), anticipations (n=4); toothbrushing task: mainly perserverations. |
| Schwartz et al. (1995) | Role of semantic knowledge | ADS patient (N=1) | Making a cup of coffee, tooth brushing | More errors on the coffee making (56 errors) compared to on the tooth brushing task (18 errors); coffee making task: object substitutions or using objects in the wrong way (48/56 errors), few omissions and perseverations; toothbrushing task: object errors (12/18 errors). |
| Schwartz et al. (Schwartz et al., 1999b) | Naturalistic action performance of patients with right hemisphere stroke | Patients with right hemisphere stroke (N=30) | Wrapping a gift, making toast, packing a lunchbox | Omissions (47%), sequence errors (19%). |
| Schwartz et al. (1998b) | Naturalistic action performance of patients with closed head injury | Patients with closed head injury (N=30); age- and sex matched controls (N=18) | Wrapping a gift, making toast, packing a lunchbox | Omissions (38%), sequence errors (20%). |

### 2.1.4 Mechanical problem solving

As outlined in the introduction, inability to solve mechanical problems maybe an important deficit related to apraxia. On the one hand, mechanical reasoning may be an inherent process in the planning of a tool use action, on the other hand spontaneous understanding of the physics of tools and action could compensate for apraxic deficits of tool knowledge. At present, available research on deficits of mechanical reasoning following brain damage is limited to few studies most of them are summarized below. Different from ADS symptoms than are not related to either left or right brain damage, deficits in mechanical reasoning is more severe and more frequent in patients with left brain damage and apraxia.

**Table 6 - Reports on deficits of mechanical problem solving in stroke patients**

| Source | Tasks | Main result | Other tasks |
|---|---|---|---|
| (Goldenberg & Hagmann, 1998b) | novel tools | LBD: errors in selections and application of novel tools<br>RBD: errors only during use | pantomime<br>actual tool use |
| (Hodges, Bozeat, Lambon Ralph, Patterson, & Spatt, 2000) | novel tools | semantic dementia patients: no errors with novel tools (clear errors for functional tool knowledge) | semantic memory<br>functional tool knowledge<br>etc. |
| (Spatt, Bak, Bozeat, Patterson, & Hodges, 2002) | novel tools | cortico-basal degeneration patients: errors | see above |
| (Osiurak et al., 2008) | unusual use of daily objects | LBD: deficits during unusual use | conventional tool use<br>etc. |

## 2.2 Activities of Daily Living and Apraxia

Studies on the performance of AADS patients in their daily-living outside the lab are extremely rare. Some studies proved the disturbing effects of apraxia on daily living performance using questionnaires completed by the patients, relatives or caregivers (Smania et al., 2006). Heugten et al. (2000) assessed ADL performance of stroke survivors in occupational therapy departments in general hospitals, rehabilitation centres, and nursing homes. They found a high correlation between ADL impairments and apraxia scores revealed from standard clinical tests. A coarse assessment of ADL performance at home or at the clinical ward is provided by the Functional Independence Measure (FIM). Using the FIM score as an outcome variable, a correlation between outcome and apraxia was established (Giaquinto et al., 1999). A comparable approach measured the amount of caregiver assistance on the Physical Self-Maintenance Scale (PSMS) and again found correlation with formal tests of apraxia (Hanna-Pladdy, Heilman, & Foundas, 2003). Finally, a recent study in a large group of stroke patients (N=635) noted a relatively low but consistent correlation between a multi-step action and functional independence measures such as the Barthel index or the Nottingham Extended ADL Scale (Bickerton, Riddoch, Samson, Balani, Mistry, Humphreys, (2012).

An attempt to quantitatively analyse ADL performance in apraxic patients was provided by Foundas et al. (1995). These authors measured execution time and quantified performance success during the meal received at the hospital. Analysis of the performance videos revealed that apraxic LBD patients completed less successful actions in a certain amount of time and were less efficient in organizing their meal. Interestingly, the overall time was only moderately prolonged and the prolongation was not statistically significantly. The action errors during eating correlated with severity of apraxia as assessed by standard clinical testing.

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## 2.3 Models of action selection

This section describes a number of approaches to modelling psychology of sequential task execution. The models attempt to address how people learn to produce complex sequences of actions and examine possible mechanisms for the errors that occur.

Early theories of sequential action control suggested a “response chaining reflex, in which completion of one step provides excitation for the next (Watson, 1920). This claim was rejected by Lashley (1951), who proposed that successful execution of sequential tasks requires activation of a stored action-plan or *schema* and that these plans were organised hierarchically. This was supported by the observation that the performance of any action within a sequence is context dependent. For example, picking up a knife could prompt – chopping, spreading, and slicing. Lashley argued that selecting the correct action is dependent on knowledge of the overarching goal (making toast) and its component schemas (e.g., spread butter).

Following this lead, descriptions of the cognitive mechanisms underpinning routine action selection have often adopted hierarchical processing systems, which mirror the behaviour description hierarchies. As an example, Figure 4 uses a hierarchical approach to describe steps in a tea making task where, a step (e.g., lift teapot) is grouped into sub-schemas (pour tea into a cup), which are part of the overall goal of making a cup of tea (top-down flow of activation).

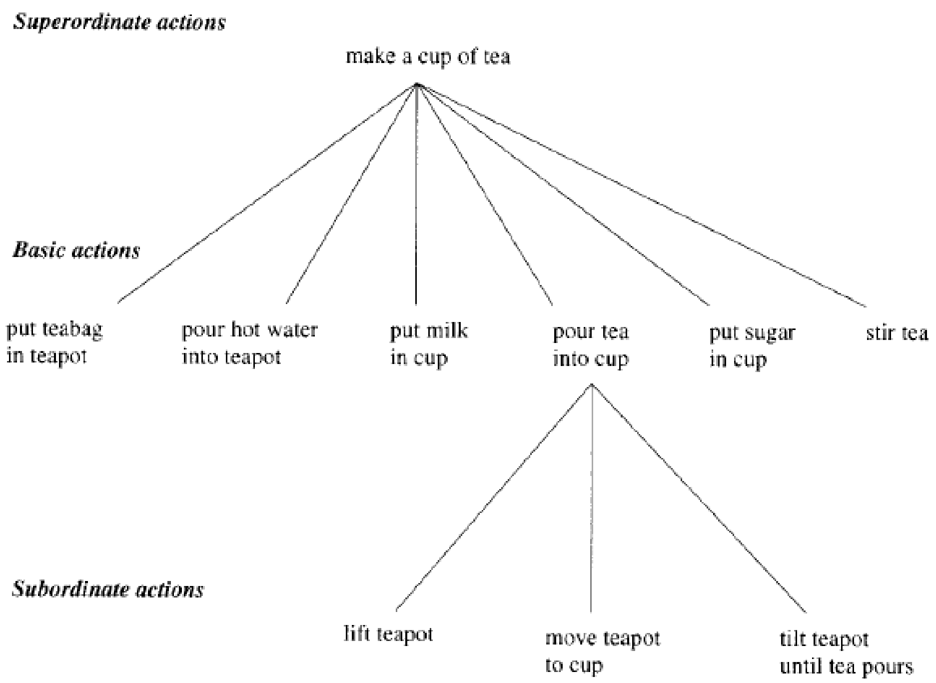


**Figure 4 - Hierarchical representation of a tea making task (Humphreys & Forde, 1998).**

### 2.3.1 Contention Scheduling Model – Norman and Shallice (1986)

Norman and Shallice (1986) proposed that action selection is understood through two processes: Routine or well-practised action – the Contention Scheduling System (CSS), and attentional, supervisory control – the Supervisory Attentional System (SAS) (see **Error! Reference source not found.**). They suggested that actions are represented as schemas and that *Contention Scheduling* is the basic mechanism by which one schema is selected over another, competing schema.

- Selection is dependent on its schema being activated above threshold.
- Schemas are triggered by both top-down and environmental stimuli, enabling performance of the appropriate action and its timing.
- Selection of a schema activates its hierarchical ‘component’ schemas and/or controls the carrying out of actions.
- When an action sequence is carried out, the component schemas form a “horizontal thread” (see Figure 5). This is essentially a processing structure that enables the routine action to be carried out without intervention.

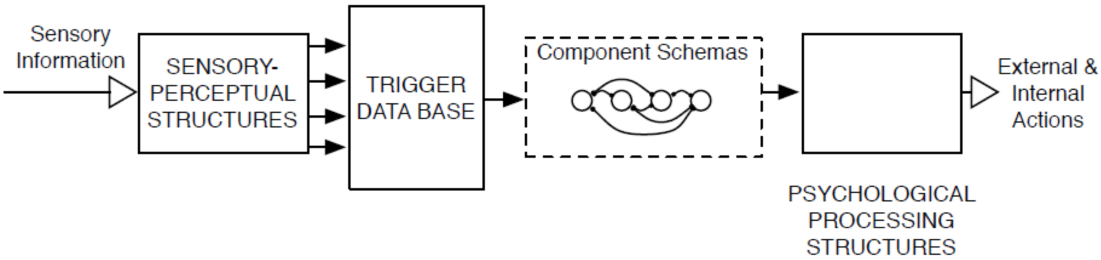


**Figure 5 - Horizontal thread from the Contention Scheduling System (Norman & Shallice, 1986)**

Norman and Shallice (1986) proposed that attention is not essential for routine action to be carried out. Rather, attention modulates action selection from the SAS. This forms a “vertical thread” (Figure 6), which is activated when attention to a task is needed, or a novel task performed.

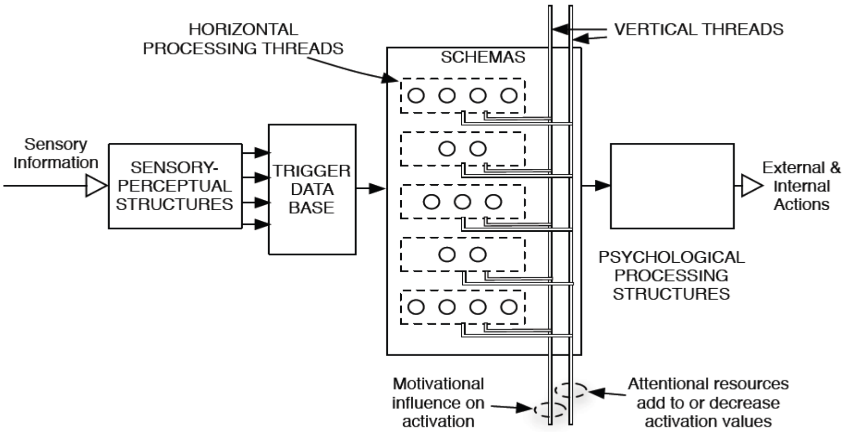


**Figure 6 - Vertical and horizontal threads (Norman & Shallice, 1986)**

Errors:

The contention scheduling model can explain action errors or 'slips' that people make performing routine tasks. 'Capture errors' occur when environmental cues for a different, but familiar, action 'capture' behaviour - for example, logging into a personal email account using work login details. These errors can be explained by suggesting that they occur when insufficient attention is paid to the intended task, thus inviting a response that is equally appropriate given the environmental conditions; suggesting that the SAS is a separate system to the CSS.

### 2.3.2 Interactive Activation Model (IAN): A computational model of the contention scheduling theory of routine action (Cooper and Shallice, 2000).

As an instantiation of the Norman and Shallice model, the Interactive activation model (IAN) model is based on 'competitive activation within a hierarchically organised network of action schemas' (Cooper & Shallice, 2000).

Figure 7 illustrates the main functional subcomponents of Cooper and Shallice's implementation of contention scheduling.

- The central part of the model is the schema network, in which individual nodes correspond to action schemas.
- Each node has an activation value and activations interact through a variety of excitatory and inhibitory mechanisms.
- Activation occurs when a node exceeds a given threshold and activation can occur from four different sources: top down influence, environmental influence, lateral influence, and self-influence.

- Selection of a high level schema e.g. ‘make coffee’, results in high excitation of component schema.
- Selection of a low level schema, e.g., ‘pick up spoon’ enables allocation of object representation and resources (from two separate networks), followed by action execution.

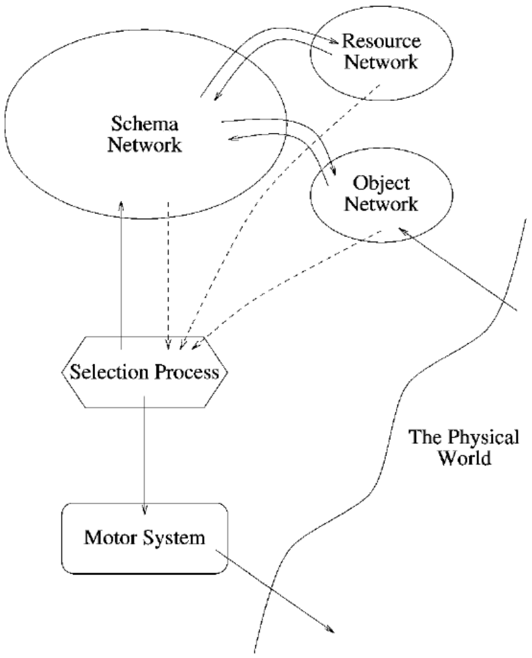


**Figure 7 - The principal components of the contention scheduling implementation (Cooper & Shallice, 2000)**

The IAN was modelled using a ‘prepare instant coffee’ task (used by Schwartz et al. 1991, 1998 in their behavioural studies). A hierarchical model of the task is shown below (Figure 8).

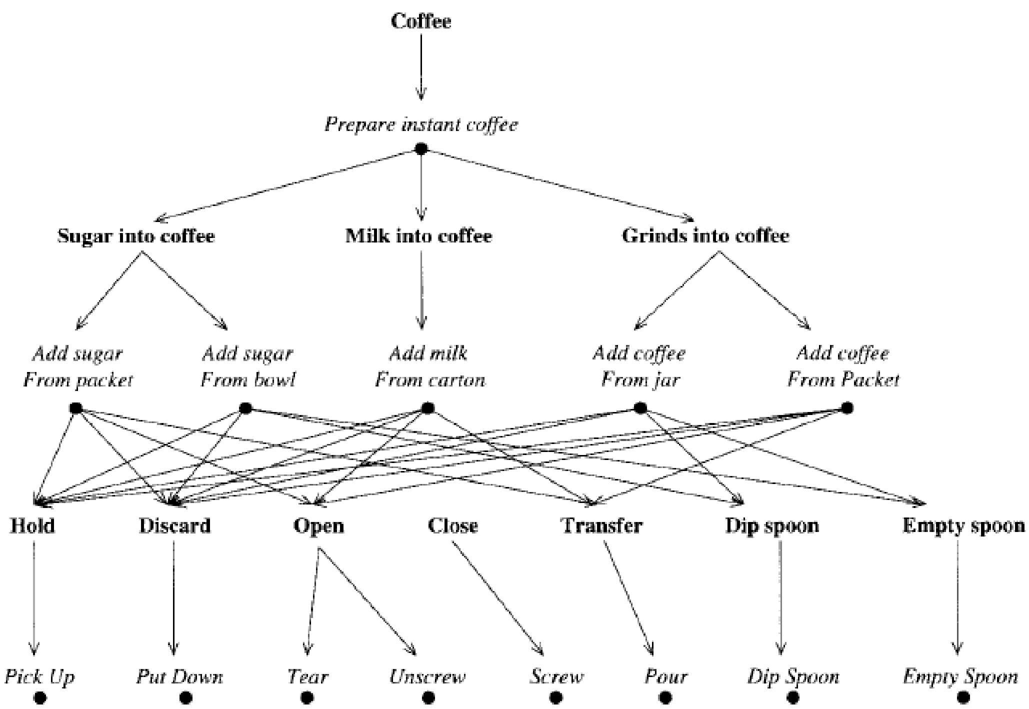


**Figure 8 - IAN processing architecture (Cooper & Shallice, 2000)**

Errors:

When the model is lesioned (by introducing random noise within the three networks) it produces behaviours and errors which are representative of the errors made by neurological patients (Schwartz, Reed, Montgomery, Palmer, & Mayer, 1991; Schwartz, 1995). Errors are produced in response to the interaction of environmental and top-down activation influences.

*Capture errors:* Occur when an environmental source of activation is relatively stronger than the top-down activation

*Perseveration errors*: Occur most frequently and are performed when a schema is not deselected. This can happen when there is too much self-activation or a lack of inhibition.

*Omission errors:* Occur due to insufficient activation of appropriate schema, poor environmental cues or self-activation.

*Anticipation errors:* Occur under the same circumstances, but the action cannot take place as a pre-condition has not been met, e.g., toast cannot be buttered if the lid is still on the butter.

### 2.3.3 Parallel Distributed Processing: Simple Recurrent Network. Botvinick and Plaut (2002, 2004)

Botvinick and Plaut (2004; 2002) proposed a radically different approach to modelling routine action selection and make a distinction between the hierarchical structure of a task and its cognitive representation. They modelled sequential behaviour using a parallel distributed processing (PDP) account (for a review see Rumelhart, McClelland, & the PDP Research Group, 2012) - a general learning mechanism which learns from samples of its environment. The model implies that understanding of task structure belongs intrinsically to the emergent properties of the processing system - unlike the identifiable structure of schemas as represented in the IAN.

- PDP models are made up of processing units (or nodes).
- The activation of each node is based on excitation and inhibition received from nodes linked to it, through weighted connections (Botvinick & Plaut, 2004).
- The network is divided into three layers (see **Error! Reference source not found.**e 9)
- An input layer - which provides a representation of the perceived environment.
- A hidden layer - which transforms the input information
- An output layer which represents the action taken – the system's response to the input.

The model is based on a *simple recurrent network (SRN)* as loops or circuits can be traced through its connections. Critically, this enables retention and transformation of information over time (Botvinick & Plaut, 2004).

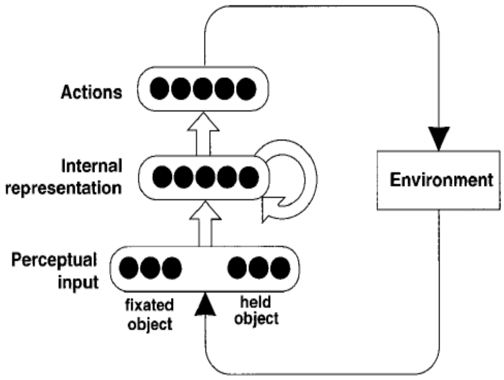


**Figure 9 - Architecture of the Simple Recurrent Network (Botvinick & Plaut, 2004)**

Simulation:

Simulations were performed to evaluate the capacity of a SRN to account for routine action selection (Botvinick & Plaut, 2004). The system was trained on both a coffee and a tea making task.

Perceptual inputs consisted of *object fixated* and *object held* and a single input and output unit for each of the object features and actions shown in Table 7 was used (and 50 hidden units). The input pattern was propagated through the hidden layer and the output pattern compared with correct output pattern for each step. The difference between the produced and correct output formed the basis for the adjustment of connection weights – thus the system 'learns' how to produce error-free performance.

The training set was run until the error rate plateaued (20,000 passes through the training set).

**Table 7 - Features and actions specific to certain objects**

*Object Features and Actions*

| Fixated input | Held input | Action |
|---|---|---|
| cup | cup | pick-up |
| 1-handle | 1-handle | put-down |
| 2-handles | 2-handles | pour |
| lid | lid | peel-open |
| clear-liquid | clear-liquid | tear-open |
| light | light | pull-open |
| brown-liquid | brown-liquid | pull-off |
| carton | carton | scoop |
| open | open | sip |
| closed | closed | stir |
| packet | packet | dip |
| foil | foil | say-done |
| paper | paper | fixate-cup |
| torn | torn | fixate-teabag |
| untorn | untorn | fixate-coffee-pack |
| spoon | spoon | fixate-spoon |
| teabag | teabag | fixate-carton |
| sugar | sugar | fixate-sugar |
| instruct-coffee | nothing | fixate-sugar bowl |
| instruct-tea | | |

Errors: When the model was lesioned, by adding random noise to activation values in the hidden layer following action selection the SRN model also produced errors which were representative of patients with neurological impairments.

*Capture errors:* Almost all errors were due to the capture process. Small increases in noise cause a drift towards a similar step.

*Omission and Anticipation errors:* Also due to capture process.

### 2.3.4 Reinforcement Model of Routine Action – Ruh, Cooper and Mareschal (2005)

Criticism of the SRN model:

Ruh, Cooper and Mareschal (2005) observed that that learning in the SRN model is entirely dependent on the training set. When training tasks share the first few inputs (see coffee and tea tasks in Botvinick & Plaut, 2004) the model is unable to determine the goal. The authors overcame this by including a further two inputs – 'instruct coffee', 'instruct tea'.

However, this adjustment leads to a separate representation of each task. This discrete representation was a major criticism of the IAN models which the SRN model attempted to overcome.

In response to this Ruh et al. (2005) proposed a reinforcement learning model. The representations function much like the SRN in Botvinick and Plaut's model (distributed representation), but their acquisition is through 'goal directed' behaviour.

Task and Model Architecture:

The model simulated a simplified version of the coffee task – the Nutella Task. The model uses actor/critic architecture (see Barto, 1995):

- The Actor is a SRN with 8 units in the input layer (see **Error! Reference source not found.**10) – representing perceived objects in the same fashion as Botvinick and Plaut's coffee task.
- The output has eight units – representing actions
- seven units in the hidden layer
- The Critic uses the same eight inputs as the Actor
- It has one output which represents the value of the perceived state
- five units in the hidden layer
- The chosen actions (outputs) are mapped onto the new inputs

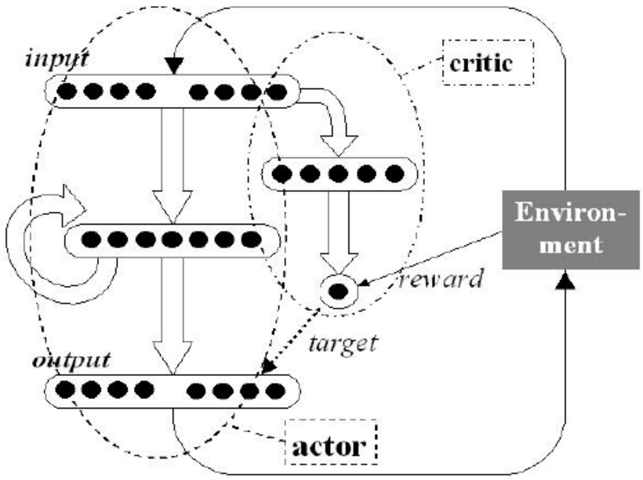


**Figure 10 - Architecture of the Reinforcement Model (Ruh et al, 2005)**

Learning:

- The critic learns to predict the value of the state determined by the output (chosen action)
- The difference between the prediction of the reward and the real next value is used to make adjustments to the weight of the critic

- The actor learns to adjust the value of its chosen output towards the critic’s predicted value.
- Importantly, only the weights which constituted to the activation of this output unit are adjusted
- Both Actor and Critic nets learn.

The fundamental difference between the SRN model and the reinforcement model is that behaviour is only reinforced in response to a valid sequence (or subsequence). The actor learns to produce reward seeking behaviours and its learning enables the critic to improve its estimate of the output value.
The system was not lesioned, so produced no error data. The authors proposed to adapt the model to sequencing tasks using multiple goals and to include the ability to switch between them (see Rougier and O’Reilly, 2002 for an example of task switching in an actor/critic architecture.

### 2.3.5 Adaptive Control of Thought Rational (ACT-R) – Byrne (2003)

- ACT-R is a cognitive architecture representing a general theory of cognition
- The model has multiple processing units - perceptual and motor modules and production system pattern matcher. Uses IF (sensory preconditions)-THEN (action) rules to specify actions to be taken and their preconditions
- Preconditions can be goals or perceptual/environmental information
- Uses information from procedural and declarative memory
- Communication between modules is managed by a memory of the system's current state - located in the buffers
- ACT-R needs two inputs - knowledge (declarative memory chunks and production rules) and environmental input (responds to actions and produces stimuli)

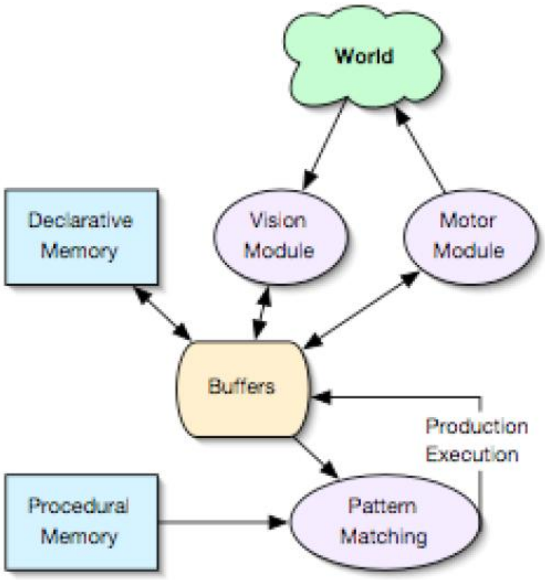


**Figure 11 - Major components of ACT-R (Byrne, 2003)**

### 2.3.6 Adaptation of the ACT-R architecture - Memory for Goals model (MFG) – Trafton (2011)

MFG assumes that sequential action is guided by episodic control codes which are generated for each step and that these codes decay with time and can be primed by contextual retrieval cues. The control codes serve a place-keeping function that allows the system to perform the correct action after performance interruption (Trafton, Altmann, & Ratwani, 2011).

Basic processing assumptions from ACT-R:

1. When central cognition asks memory - memory returns the item that is most active (most recent) in that instant.
2. Activation of a given memory fluctuates about a mean value

Additional assumptions:

- Control Codes (CC) guide performance over an individual action step. The system uses declarative knowledge to create a CC and uses CCs to guide processing for that step of the task.
- Codes serve a place-keeping function in routine action:
  Code says: "this is the step I am currently on" and thus triggers component actions
- The current step is always the most active
- After a code is encoded its activation automatically decays - therefore, retrieval is more likely to return a more recent step than an older one

- Episodic codes can also be primed by contextual retrieval cues and this overcomes effects of decay
- MFG model was implemented on an interruption experiment (participants and model simulation). The participants and the model were required to fill in an order (on a computer) for two types of sea vessels (see Trafton, Altmann, & Ratwani, 2011)
- Participants were interrupted from the primary task and were asked to complete a set of arithmetic questions.
- The ACT-R system simulated this by clearing all information about the primary task from the buffers representing mental context. The model then “spins” until the primary-task display is reinstated, after 15 seconds.

Errors:

*Perseveration errors:* Occur when an older code is retrieved in error (when there is noise in the system). Errors following interruption represent the most to least recently carried out step.

*Omission and Anticipation errors:* Occur when the retrieval of the control code resembles the *intended* step. Only if interruption occurs after the model completes a step *and* generates a control code for the following step. The model infers that the step has already been executed – so skips a step.

The model doesn’t account for capture errors.

## 2.5 Approaches to rehabilitation

The table below provides a summary of cognitive approaches towards the rehabilitation of AADS. Many of these rehabilitation methods have been shown to improve ADL functioning and can facilitate independence from caregivers. For example, task performance can be improved by providing appropriate and personalised feedback to patients (Bickerton, Humphreys, & Riddoch, 2006a; Forde & Humphreys, 2002) and by breaking tasks down into small steps (Forde & Humphreys, 2002). The effects of training have also been shown to transfer from trained to untrained tasks (Geusgens et al., 2006; Smania et al., 2006) – although some work has found no transfer of effects (Donkervoort, Dekker, Stehmann-Saris, & Deelman, 2001; Geusgens et al., 2006). Additionally, maintenance of the positive effects of treatment has been shown to depend on continuous task practice (e.g. Goldenberg & Hagmann, 1998a).

The use of smart environments as a rehabilitation tool has not been explored with AADS patients. However, work with dementia patients who had difficulty completing everyday tasks (e.g. Mihailidis, Boger, Craig, & Hoey, 2008) has shown that using a 'prompting system' can both improve task performance and patients' independence, whilst providing continuous feedback. Additionally, a recent study by Bettcher et al. (2011) suggested the potential for the introduction of a similar presentation of their training task intervention (trialled on dementia patients) on a smartphone.

**Table 8 - Summary of approaches for the cognitive rehabilitation of AADS**

| Paper | Approach | Summary of approach | Patients | Results | Treatment duration |
|---|---|---|---|---|---|
| Van Heugten et al. 1998 | Strategy training approach | Not aimed at recovery of function. Teaching of compensatory methods. External compensation: help from outside the individual, e.g., showing pictures of action steps to aid sequencing difficulties. Internal compensation: uses patients' unimpaired cognitive functions, e.g., verbalisation of a sequence of steps | 33 left-hemisphere stroke patients with apraxia | Significant improvements in ADL functioning on all measures (Bartel Index, ADL observed by OT, ADL questionnaire completed by OT). Maintenance of gains in trained tasks at 5 month follow up. | 12 weeks – number of treatment determined by therapist (between 3 and 5 half hour sessions a week). |
| Donkervoort et al. 2001 | Strategy training approach | As above: internal and external compensatory strategies | 43 left hemisphere patients with apraxia | Patients in strategy training group improved significantly more on trained ADL tasks than patients in usual treatment group (small to medium effect). No effect 5 months post-test. | 8 week treatment - follow up at 5 months |
| Maher, Rothi and Greenwald, 1991 | Multiple cues and cue withdrawal | Treatment of gestures: multimodal cues – tools and objects, visual cues, feedback. Cues were withdrawn as performance improved | 55 year old male – chronic ideomotor apraxia | Significant improvement in treated gestures. | 1 hour daily for 2 weeks. |

| Paper | Approach | Summary of approach | Patients | Results | Treatment duration |
|---|---|---|---|---|---|
| Pilgrim and Humphreys 1994 | Conductive education | Physical manipulation and verbalisation of individual task steps. Cues withdrawn as performance improved | 1 patient – Apraxia of non-dominant limb | Significant improvement on trained tasks (compared to untrained tasks). No generalisation to untreated objects. | 15 minutes daily for 3 weeks |
| Smania et al, 2000 | Transitive/intransitive gesture training | Transitive gesture training: i)shown how to use common tools, ii) shown a picture of part of the gesture and asked to pantomime, iii) shown a picture of the tool and asked to produce gesture. Intransitive gesture training: i) shown a context and a gesture picture, ii) shown a context picture alone, iii) shown a different context. In all 3 phases patients were asked to reproduce the gesture. | 22 patients with ideomotor apraxia | Performance significantly improved relative to control group (aphasia treatment only) – Ideomotor Apraxia Test (IMA), gesture comprehension test and ADL test | 50 minutes, 3 times a week for 10 weeks |
| Goldenberg and Hagmann, 1998 | Errorless learning | Manipulation of limbs during ADL performance. Simultaneous performance of ADL with therapist/examiner. Patient copies therapist. Exploration training included attention to object features and functionality. | 15 patients with limb apraxia (measured by IMA) | Significant improvement on trained activities (measured by number of fatal errors). | 20-40 minutes daily for 2-5 weeks. |

| Paper | Approach | Summary of approach | Patients | Results | Treatment duration |
|---|---|---|---|---|---|
| Forde and Humphreys 2002 | Variety of approaches | Pictorial representation of the goal, written commands, one goal at a time, demonstrating task, dividing task demonstration into small subgoals | Single male patient with ADS | No significant effects on trained tasks (similar tasks had been used on another ADS patient – this patient showed significant improvement on tasks). | Experimental tasks |
| Bickerton, Humphreys and Riddoch 2006 | Verbalisation strategy | Patient taught a poem based on the steps of making a cup of tea | Single male patient with ADS | Significant improvement on order of actions in tea making task. Weak training effects across sessions and no transfer to untrained tasks/objects. | Trained over 13 sessions |
| Mihailidis et al. 2008 | Smart environment | A computerized device - COACH, uses artificial intelligence to guide patients through a hand washing task using audio and/or audio-video prompts. | 6 dementia patients | Patients able to complete an average of 11% more hand washing steps independently and needed 60% less interaction with a caregiver | 20 trials (using COACH) |
| Bettcher et al. 2011 | Error monitoring/detection.<br>Task Training Action Intervention: TT - NAT | Pictorial descriptions of objects – with a script of the role of the object in the task. Video presentation of task, from a patient's perspective. | 45 dementia patients | Patients administered TT-NAT made significantly fewer errors and detected significantly more errors on the Naturalistic Action Test (NAT) than those in the control group (NAT only). | A brief training session prior to each task on the NAT |

# 3. CONCLUSIONS

The summary of the literature in this report addressed different topics relevant for the CogWatch project. In the Introduction the clinical features and the aetiology of apraxia and action disorganization syndrome were summarized. The following review concentrated on those aspects that are relevant for the realization of the cognitive rehabilitation system.

Studies on the performance of apraxic patients during the use of single tools emphasize the role of the left hemisphere in these tasks. They also show that actual task performance is usually less compromised than out-of-context performance such as generating a pantomime of a tool-use action. Nevertheless the majority of the studies prove the existence of performance deficits even in seemingly simple task such as hammering or sawing in a substantial number of patients and despite the complete context is provided. Even if pantomime performance is not directly relevant as an aspect of the rehabilitation approach, it is nevertheless a critical test in the testing protocol since it may help to identify potentially suitable patients and to see how progress in rehabilitation transfers to more basic aspects of apraxia.

Interpreting data on a patient's movement in order to recognize the action and to determine if an action is correct, can be critically affected by more elementary deficits of the patients in performing goal-directed movements. Corresponding studies indeed revealed that goal-direct movements such as pointing or grasping or visuomotor adaptation can be impaired even in the hand ipsilateral to the lesion that is not affected by a primary motor deficit such as paresis. Notably, in the cited tasks the deficits depend on the side of the brain damage: Damage to the right brain tends to prolong reaction times and to reduce accuracy, while damage to the left brain disturbs more dynamic aspects of the movements. In more complex tasks such dependencies on the side of the brain damage are less obvious. Two consequences seem meaningful for the design of the rehabilitation system: Either the action recognition system should not be sensitive to corresponding movement deficits, or the system should be capable of capturing multiple performance characteristics and differentiate their relevance for goal achievement. In the former case analysis would be more event based, in the later the analyses would include evaluation of trajectories.

The kinematic approach has also turned out to be useful in studies of actual tool use in patients. These analyses are more sensitive than scoring systems. As is obvious from the summarized studies on this approach, the cost of the high sensitivity is problems in assessing other complex features of performance. Thus it has to be demonstrated whether a more complete tracking of the body segments and objects in manipulation tasks can enable automatic decoding of more complex aspects of action. This approach would enable the investigation of the relationship between movement qualities such as smoothness and goal achievement.

Most relevant for CogWatch are studies on multiple-step action with multiple tools and objects. Such demands are most typical for activities of daily living. Corresponding studies have revealed partly severe performance deficits in patients during ADL activities. Importantly, deficits that can be linked to apraxia and deficits that can be linked to action disorganization syndrome merge so that frequently no clear attribution to one or other of the syndromes is possible. While apraxic disorders are more frequently related to left brain damage, ADS is not clearly related to one particular hemisphere. Importantly the studies showed a whole variety of different errors that may prevent or slow down the attainment of the goal. Nevertheless some errors types outnumbered others, in particular omission errors and perseverations occurred particularly frequent during the execution of multi-step actions. Consequently the CogWatch system should be sensitive to these kinds of errors.

Error detection in a cognitive rehabilitation system depends on knowledge about correct execution of action. In multi-step actions the relationship between sub-components can be very complex. Various models have been devised to simulate normal performance in such tasks. Such models can be used for the development of action recognition systems. The summary of models provides different approaches to be evaluated for their usefulness for CogWatch.

As is apparent from the summarized studies of cognitive rehabilitation in AADS, intervention by therapists can be successful. However, the review has uncovered only a very few instances of ICT-based cognitive rehabilitation such as CogWatch. Only in the area of dementia have a few systems, based on roughly comparable approaches, been published so far (see 2.5). In this respect, cognitive rehabilitation lags behind motor rehabilitation. In the later field, ICT-based systems are a major interest of research and also are already established successfully in clinical practice (e.g., Hesse et al., 2005; Mehrholz, Werner, Kugler, & Pohl, 2007; Krebs et al., 2008). Thus, while cognitive training of AADS symptoms by therapist has been proven successfully, approaches basing on automated systems using modern technology such as CogWatch are missing.

## 3.1 Publication strategy

From the above summaries of the literature several topics for potential publication as reviews became obvious. These topics are indicated below. Some of these publications are currently being prepared for submission.

- Sequential error classification
- Models of errors in sequential tasks
- Eye movements in sequential tasks
- Cueing in rehabilitation of sequential task performance
- Neural basis of sequential action
- Tool use: neural representation of tool use
- Tool use 2: impairments of real tool use and everyday actions

# 4. REFERENCES


Agostoni, E., Coletti, A., Orlando, G., & Tredici, G. (1983). Apraxia in deep cerebral lesions. *Journal of Neurology, Neurosurgery & Psychiatry,* 46*,* 804-808.

Barbieri, C. & De Renzi, E. (1988). The executive and ideational components of apraxia. *Cortex,* 24*,* 535-543.

Barto, A. G. (1995). Adaptive critics and the basal ganglia. In J.C.Houk, J. L. Davis, & D. G. Beiser (Eds.), *Models of information Processing in the Basal Ganglia* (pp. 214-232). Cambridge, MA: MIT Press.

Bartolo, A., Cubelli, R., Della Sala, S., & Drei, S. (2003). Pantomimes are special gestures which rely on working memory. *Brain and Cognition,* 53*,* 483-494.

Basso, A., Luzzatti, C., & Spinnler, H. (1980). Is ideomotor apraxia the outcome of damage to well defined regions of the left hemisphere? *Journal of Neurology, Neurosurgery and Psychiatry,* 43*,* 118-126.

BAY, E. (1962). Aphasia and non-verbal disorders of language. *Brain,* 85*,* 411-426.

Belanger, S. A., Duffy, R. J., & Coelho, C. A. (1996). The assessment of limb apraxia - an investigation of task effects and their cause. *Brain and Cognition,* 32*,* 384-404.

Bettcher, B. M., Giovannetti, T., Libon, D. J., Eppig, J., Wambach, D., & Klobusicky, E. (2011). Improving everyday error detection, one picture at a time: a performance-based study of everyday task training. *Neuropsychology.,* 25*,* 771-783.

Bickerton, W. L., Humphreys, G. W., & Riddoch, J. M. (2006a). The use of memorised verbal scripts in the rehabilitation of action disorganisation syndrome. *Neuropsychol.Rehabil.,* 16*,* 155-177.

Bickerton, W. L., Humphreys, G. W., & Riddoch, M. J. (2006b). The use of memorised verbal scripts in the rehabilitation of action disorganisation syndrome. *Neuropsychological Rehabilitation,* 16*,* 155-177.

Bickerton, W. L., Riddoch, M. J., Samson, D., Balani, A. B., Mistry, B., & Humphreys, G. W. (2012). Systematic assessment of apraxia and functional predictions from the Birmingham Cognitive Screen (BCoS). *Journal of Neurology, Neurosurgery and Psychiatry,* in press.

Bickerton, W. L., Samson, D., Williamson, J., & Humphreys, G. W. (2011). Separating forms of neglect using the Apples Test: validation and functional prediction in chronic and acute stroke. *Neuropsychology.,* 25*,* 567-580.

Bickerton, W. L., Humphreys, G. W., & Riddoch, M. (2007). The case of the unfamiliar implement: Schema-based over-riding of semantic knowledge from objects in everyday action. *Journal of the International Neuropsychological Society,* 13*,* 1035-1046.

Boronat, C. B., Buxbaum, L. J., Coslett, H. B., Tang, K., Saffran, E. M., Kimberg, D. Y., & Detre, J. A. (2005). Distinctions between manipulation and function knowledge of objects: evidence from functional magnetic resonance imaging. *Cognitive Brain Research,* 23*,* 361-373.

Botvinick, M. & Plaut, D. C. (2002). Representing task context: proposals based on a connectionist model of action. *Psychol.Res,* 66*,* 298-311.

Botvinick, M. & Plaut, D. C. (2004). Doing Without Schema Hierarchies: A Recurrent Connectionist Approach to Normal and Impaired Routine Sequential Action. *Psychological Review,* 111*,* 395-429.

Buxbaum, L. J. (1998). Ideational apraxia and naturalistic action. *Cognitive Neuropsychology,* 15*,* 617-643.

Buxbaum, L. J., Giovannetti, T., & Libon, D. (2000). The role of the dynamic body schema in praxis: evidence from primary progressive apraxia. *Brain and Cognition,* 44*,* 166-191.

Buxbaum, L. J. & Saffran, E. M. (2002). Knowledge of object manipulation and object function: dissociations in apraxic and nonapraxic subjects. *Brain Lang,* 82*,* 179-199.

Buxbaum, L. J., Schwartz, M. F., & Carew, T. G. (1997). The role of semantic memory in object use. *Cognitive Neuropsychology,* 14*,* 219-254.

Buxbaum, L. J., Schwartz, M. F., & Montgomery, M. W. (1998). Ideational apraxia and naturalistic action. *Cognitive Neuropsychology,* 15*,* 617-643.

Byrne, M. D. A mechanism-based framework for predicting routine procedural errors. R.Alterman and D.Kirsh. Proceedings of the25th Annual Conference of the Cognitive Science Society . 2003. Austin, TX, Cognitive Science Society.

Ref Type: Abstract

Canavan, A. G. M., Passingham, R. E., Marsden, C. D., Quinn, N., Wyke, M., & Polkey, C. E. (1989). Sequencing ability in Parkinsonians, patients with frontal lobe lesions and patients who have undergone unilateral temporal lobectomies. *Neuropsychologia,* 27*,* 787-798.

Carmo, J. C. & Rumiati, R. I. (2009). Imitation of transitive and intransitive actions in healthy individuals. *Brain Cogn,* 69*,* 460-464.

Clark, M. A., Merians, A. S., Kothari, A., Poizner, H., Macauley, B., Rothi, L. J. G., & Heilman, K. M. (1994). Spatial planning deficits in limb apraxia. *Brain,* 117*,* 1093-1106.

Colebatch, J. G. & Gandevia, S. C. (1989). The distribution of muscular weakness in upper motor neurone lesions affecting the arm. *Brain,* 112*,* 749-763.

Cooper, R. & Shallice, T. (2000). Contention scheduling and the control of routine activities. *Cogn Neuropsychol.,* 17*,* 297-338.

Cooper, R. P., Schwartz, M. F., Yule, P., & Shallice, T. (2005). The simulation of action disorganisation in complex activities of daily living. *Cognitive Neuropsychology,* 22*,* 959-1004.

Cubelli, R., Marchetti, C., Boscolo, C., & Della Sala, S. (2000). Cognition in action: testing a model of limb apraxia. *Brain and Cognition,* 44*,* 144-165.

De Renzi, E. (1990). Apraxia. In F.Boller & J. Grafman (Eds.), *Handbook of Clinical Neuropsychology* (pp. 245-263). Amsterdam, New York, Oxford: Elsevier.

De Renzi, E., Faglioni, P., Lodesani, M., & Vecchi, A. (1983). Performance of left brain-damaged patients on imitation of single movements and motor sequences. Frontal and parietal-injured patients compared. *Cortex,* 19*,* 333-343.

De Renzi, E., Faglioni, P., & Sorgato, P. (1982). Modality-specific and supramodal mechanisms of apraxia. *Brain,* 105*,* 301-312.

De Renzi, E. & Luchelli, F. (1988). Ideational apraxia. *Brain,* 111*,* 1173-1185.

De Renzi, E., Motti, F., & Nichelli, P. (1980). Imitating gestures: A quantitative approach to ideomotor apraxia. *Archives of Neurology,* 37*,* 6-10.

De Renzi, E., Pieczuro, A., & Vignolo, L. A. (1968). Ideational apraxia: A quantitative study. *Neuropsychologia,* 6*,* 41-52.

Donkervoort, M., Dekker, J., Stehmann-Saris, F. C., & Deelman, B. G. (2001). Efficacy of strategy training in left hemisphere stroke patients with apraxia: a randomized clinical trial. *Neuropsychological Rehabilitation,* 11*,* 549-566.

Duffy, R. J. & Duffy, J. R. (1989). An investigation of body part as object (BPO) responses in normal and brain-damaged adults. *Brain Cogn,* 10*,* 220-236.

Duffy, R. J., Watt, J. H., & Duffy, J. R. (1994). Testing causal theories of pantomimic deficits in aphasia using path analysis. *Aphasiology,* 8*,* 361-379.

Ekman, P. & Friesen, W. V. (1969). The repertoire of nonverbal behavior: categories, origins, usage, and coding. *Semiotica,* 1*,* 49-89.

Fisk, J. D. & Goodale, M. A. (1988). The effects of unilateral brain damage on visually guided reaching: hemispheric differences in the nature of the deficit. *Experimental Brain Research,* 72*,* 425-435.

Forde, E. M. E. & Humphreys, G. W. (2000). The role of semantic knowledge and working memory in everyday tasks. *Brain and Cognition,* 44*,* 214-252.

Forde, E. M. E. & Humphreys, G. W. (2002). Dissociations in routine behaviour across patients and everyday tasks. *Neurocase, 8,* 151-167.

Forde, E. M. E., Humphreys, G. W., & Remoundou, M. (2004). Disordered knowledge of action order in action disorganisation syndrome. *Neurocase, 10,* 19-28.

Foundas, A. L., Macauley, B. L., Raymer, A. M., Maher, L. M., Heilman, K. M., & Rothi, L. J. G. (1995). Ecological implications of limb apraxia: evidence from mealtime behavior. *Journal of the International Neuropsychological Society, 1,* 62-66.

Geschwind, N. & Damasio, A. R. (1985). Apraxia. In J.A.M.Frederiks (Ed.), *Handbook of clinical neuropsychology* (pp. 423-432). Amsterdam, New York: Elsevier.

Geusgens, C., van, H. C., Donkervoort, M., van den Ende, E., Jolles, J., & van den Heuvel, W. (2006). Transfer of training effects in stroke patients with apraxia: an exploratory study. *Neuropsychol.Rehabil., 16,* 213-229.

Giaquinto, S., Buzzelli, S., Difrancesco, L., Lottarini, A., Montenero, P., Tonin, P., & Nolfe, G. (1999). On the Prognosis of Outcome After Stroke. *Acta Neurologica Scandinavica, 100,* 202-208.

Giovannetti, T., Schwartz, M. F., & Buxbaum, L. J. (2007). The Coffee Challenge: A new method for the study of everyday action errors. *Journal of Clinical and Experimental Neuropsychology, 29,* 690-705.

Goldenberg, G. (1995). Imitating gestures and manipulating a mannikin - the representation of the human body in ideomotor apraxia. *Neuropsychologia, 33,* 63-72.

Goldenberg, G. (1996). Defective imitation of gestures in patients with damage in the left or right hemispheres. *Journal of Neurology, Neurosurgery and Psychiatry, 61,* 176-180.

Goldenberg, G. (1999). Matching and imitation of hand and finger postures in patients with damage in the left or right hemispheres. *Neuropsychologia, 37,* 559-566.

Goldenberg, G. (2003a). Apraxia and beyond: Life and work of Hugo Liepmann. *Cortex, 39,* 509-524.

Goldenberg, G. (2003b). Pantomime of object use: a challenge to cerebral localization of cognitive function. *NeuroImage, 20,* S101-S106.

Goldenberg, G. & Hagmann, S. (1997). The meaning of meaningless gestures: a study of visuo-imitative apraxia. *Neuropsychologia, 35,* 333-341.

Goldenberg, G. & Hagmann, S. (1998a). Therapy of activities of daily living in patients with apraxia. *Neuropsychological Rehabilitation, 8,* 123-141.

Goldenberg, G. & Hagmann, S. (1998b). Tool use and mechanical problem solving in apraxia. *Neuropsychologia, 36,* 581-589.

Goldenberg, G., Hartmann, K., & Schlott, I. (2003). Defective pantomime of object use in left brain damage: apraxia or asymbolia? *Neuropsychologia, 41,* 1565-1573.

Goldenberg, G., Hartmann-Schmid, K., Sürer, F., Daumüller, M., & Hermsdörfer, J. (2007). The impact of dysexecutive syndrome on use of tools and technical devices. *Cortex, 43,* 424-435.

Goldenberg, G., Hentze, S., & Hermsdörfer, J. (2004). The effect of tactile feedback on pantomime of tool use in apraxia. *Neurology,* 63*,* 1863-1867.

Goldenberg, G., Hermsdörfer, J., Glindemann, R., Rorden, C., & Karnath, H. O. (2007). Pantomime of tool use depends on integrity of left inferior frontal cortex. *Cerebral Cortex,* 17*,* 2769-2776.

Goldenberg, G. & Karnath, H. O. (2006). The neural basis of imitation is body part specific. *J Neurosci,* 26*,* 6282-6287.

Goldenberg, G., Laimgruber, K., & Hermsdörfer, J. (2001). Imitation of gestures by disconnected hemispheres. *Neuropsychologia,* 39*,* 1432-1443.

Goldenberg, G. & Spatt, J. (2009). The neural basis of tool use. *Brain,* 132*,* 1645-1655.

Goldenberg, G. & Strauss, S. (2002). Hemisphere asymmetries for imitation of novel gestures. *Neurology,* 59*,* 893-897.

Goldenberg, G., Wimmer, A., Auff, E., & Schnaberth, G. (1986). Impairment of motor planning in patients with Parkinson`s disease: evidence from ideomotor apraxia testing. *Journal of Neurology, Neurosurgery and Psychiatry,* 49*,* 1266-1272.

Goodale, M. A., Jakobson, L. S., & Keillor, J. M. (1994). Differences in the visual control of pantomimed and natural grasping movements. *Neuropsychologia,* 32*,* 1159-1178.

Graff-Radford, N. R., Welsh, K., & Godersky, J. (1987). Callosal apraxia. *Neurology,* 37*,* 100-105.

Haaland, K. Y. & Harrington, D. (1989). The role of the hemispheres in closed loop movements. *Brain and Cognition,* 9*,* 158-180.

Haaland, K. Y. & Harrington, D. L. (1994). Limb-sequencing deficits after left but not right hemisphere damage. *Brain and Cognition,* 24*,* 104-122.

Haaland, K. Y., Harrington, D. L., & Knight, R. T. (2000). Neural representations of skilled movement. *Brain,* 123*,* 2306-2313.

Haaland, K. Y., Schaefer, S. Y., Knight, R. T., Adair, J. C., Magalhaes, A., Sadek, J., & Sainburg, R. L. (2009). Ipsilesional trajectory control is related to contralesional arm paralysis after left hemisphere damage. *Experimental Brain Research,* 196*,* 195-204.

Haaland, K. Y. & Flaherty, D. (1984). The different types of limb apraxia errors made by patients with left vs. right hemisphere damage. *Brain and Cognition,* 3*,* 370-384.

Hanna-Pladdy, B., Heilman, K. M., & Foundas, A. L. (2003). Ecological implications of ideomotor apraxia: evidence from physical activities of daily living. *Neurology,* 60*,* 487-490.

Harrington, D. L. & Haaland, K. Y. (1992). Motor sequencing with left-hemisphere damage - are some cognitive deficits specific to limb apraxia? *Brain,* 115*,* 857-874.

Hartmann, K., Goldenberg, G., Daumüller, M., & Hermsdörfer, J. (2005). It takes the whole brain to make a cup of coffee: the neuropsychology of naturalistic actions involving technical devices. *Neuropsychologia,* 43*,* 625-637.

Heilman, K. M., Maher, L. H., Greenwald, M. L., Rothi, L. J. G., & Maher, L. M. (1997). Conceptual apraxia from lateralized lesions. *Neurology,* 49*,* 457-464.

Heilman, K. M. & Rothi, L. J. G. (1993). Apraxia. In K.M.Heilman & E. Valenstein (Eds.), *Clinical Neuropsychology* (3 ed., pp. 141-163). New York, Oxford: Oxford University Press.

Hermsdörfer, J., Blankenfeld, H., & Goldenberg, G. (2003). The dependence of ipsilesional aiming deficits on task demands, lesioned hemisphere, and apraxia. *Neuropsychologia,* 41*,* 1628-1643.

Hermsdörfer, J., Hentze, S., & Goldenberg, G. (2006). Spatial and kinematic features of apraxic movement depend on the mode of execution. *Neuropsychologia,* 44*,* 1642-1652.

Hermsdörfer, J., Laimgruber, K., Kerkhoff, G., Mai, N., & Goldenberg, G. (1999). Effects of unilateral brain damage on grip selection, coordination, and kinematics of ipsilesional prehension. *Experimental Brain Research,* 128*,* 41-51.

Hermsdörfer, J., Li, Y., Randerath, J., Goldenberg, G., & Johansson, L. (2012). Tool use without a tool: kinematic characteristics of pantomiming as compared to actual use and the effect of brain damage. *Experimental Brain Research,* in press.

Hermsdörfer, J., Li, Y., Randerath, J., Roby-Brami, A., & Goldenberg, G. (2012). Tool use kinematics across different modes of execution. Implications for action representation and apraxia. *Cortex,* in press.

Hermsdörfer, J., Mai, N., Spatt, J., Marquardt, C., Veltkamp, R., & Goldenberg, G. (1996). Kinematic analysis of movement imitation in apraxia. *Brain,* 119*,* 1575-1586.

Hermsdörfer, J., Ullrich, S., Marquardt, C., Goldenberg, G., & Mai, N. (1999). Prehension with the ipsilesional hand after unilateral brain damage. *Cortex,* 35*,* 139-161.

Hesse, S., Werner, C., Pohl, M., Rueckriem, S., Mehrholz, J., & Lingnau, M. L. (2005). Computerized arm training improves the motor control of the severely affected arm after stroke: a single-blinded randomized trial in two centers. *Stroke,* 36*,* 1960-1966.

Heugten, C. M. v., Dekker, J., Deelman, B. G., Vandijk, A. J., Stehmann-Saris, F. C., & Kinebanian, A. (2000). Measuring Disabilities in Stroke Patients with Apraxia - A Validation-Study of an Observational Method. *Neuropsychological Rehabilitation,* 10*,* 401-414.

Hillis, A. E., Wityk, R. J., Barker, P. B., Beauchamp, N. J., Gailloud, P., Murphy, K., Cooper, O., & Metter, E. J. (2002). Subcortical aphasia and neglect in acute stroke: the role of cortical hypoperfusion. *Brain, 125,* 1094-1104.

Hodges, J. R., Bozeat, S., Lambon Ralph, M. A. L., Patterson, K., & Spatt, J. (2000). The role of conceptual knowledge in object use - Evidence from semantic dementia. *Brain, 123,* 1913-1925.

Hodges, J. R., Spatt, J., & Patterson, K. (1999). What and how - Evidence for the dissociation of object knowledge and mechanical problem-solving skills in the human brain. *Proceedings of the National Academy of Sciences of the United States of America, 96,* 9444-9448.

Humphreys, G. W. & Forde, E. M. E. (1998). Disordered action schema and action disorganisation syndrome. *Cognitive Neuropsychology, 15,* 771-811.

Humphreys, G. W., Forde, E. M. E., & Riddoch, M. J. (2001). The planning and execution of everyday actions. In B.Rapp (Ed.), *The handbook of cognitive neuropsychology: What deficits reveal about the human mind* (pp. 565-589). Psychology Press.

Husain, M. & Rorden, C. (2003). Non-spatially lateralized mechanisms in hemispatial neglect. *Nat.Rev.Neurosci., 4,* 26-36.

Jones, R. D., Donaldson, I. M., & Parkin, P. J. (1989). Impairment and recovery of ipsilateral sensory-motor function following unilateral cerebral infarction. *Brain, 112,* 113-132.

Kazui, S. & Sawada, T. (1993). Callosal apraxia without agraphia. *Annals of Neurology, 33,* 401-403.

Kendon, A. (2004). *Gesture - Visible Action as Utterance*. Cambridge, NewYork: Cambridge University Press.

Kimura, D. (1977). Acquisition of a motor skill after left-hemisphere damage. *Brain, 100,* 527-542.

Kimura, D. & Archibald, Y. M. (1974). Motor functions of the left hemisphere. *Brain, 97,* 337-350.

Krebs, H. I., Dipietro, L., Levy-Tzedek, S., Fasoli, S. E., Rykman-Berland, A., Zipse, J., Fawcett, J. A., Stein, J., Poizner, H., Lo, A. C., Volpe, B. T., & Hogan, N. (2008). A Paradigm Shift for Rehabilitation Robotics. Therapeutic Robots Enhance Clinician Productivity in Facilitating Patient Recovery. *IEEE Engineering in Medizine and Biology Magazine, 27,* 61-70.

Laimgruber, K., Goldenberg, G., & Hermsdörfer, J. (2005). Manual and hemispheric asymmetries in the execution of actual and pantomimed prehension. *Neuropsychologia, 43,* 682-692.

Lashley, K. S. (1951). The problem of serial order in behavior. In *Cerebral mechanisms in behavior* (pp. 112-136). New York: Wiley.

Lehmkuhl, G. & Poeck, K. (1981). A disturbance of the conceptual organisation of actions in patients with ideational apraxia. *Cortex,* 17*,* 153-158.

Liepmann, H. (1900). Das Krankheitsbild der Apraxie ("motorischen Asymbolie") auf Grund eines Falles einseitiger Apraxie. *Monatsschrift für Psychiatrie und Neurologie,* 8*,* 15-44,102-132,182-197.

Liepmann, H. (1908). *Drei Aufsätze aus dem Apraxiegebiet*. Berlin: Karger.

Marangolo, P., De Renzi, E., Dipace, E., Ciurli, P., & Castriota-Skandenberg, A. (1998). Let not thy left hand know what thy right hand knoweth. The case of a patient with an infarct involving the callosal pathways. *Brain,* 121*,* 1459-1467.

Mayer, N. H., Reed, E., Schwartz, M. F., Montgomery, M., & Palmer, C. (1990). Buttering a hot cup of coffee: An approach to the study of errors of action in patients with brain damage. In D.E.Tupper & K. D. Cicerone (Eds.), *The Neuropsychology of Everyday Life: Assessment and Basic Competencies* (pp. 259-284). Boston Dordrecht London: Kluwer Academic Publishers.

McDonald, S., Tate, R. L., & Rigby, J. (1994). Error types in Ideomotor Apraxia: a qualitative analysis. *Brain and Cognition,* 25*,* 250-270.

McNeill, D. (1992). *Hand and mind*. Chicago, London: The University of Chicago Press.

Mehler, M. F. (1987). Visuo-imitative apraxia. *Neurology,* 37(s1)*,* 129.

Mehrholz, J., Werner, C., Kugler, J., & Pohl, M. (2007). Electromechanical-assisted training for walking after stroke. *Cochrane.Database.Syst.Rev.,* CD006185.

Mihailidis, A., Boger, J. N., Craig, T., & Hoey, J. (2008). The COACH prompting system to assist older adults with dementia through handwashing: an efficacy study. *BMC.Geriatr.,* 8*,* 28.

Morady, K. & Humphreys, G. (2009). Comparing action disorganization syndrome and dual-task load on normal performance in everyday action tasks. *Neurocase,* 15*,* 1-12.

Morady, K. & Humphreys, G. (2011). Multiple task demands in action disorganization syndrome. *Neurocase,* 17*,* 461-472.

Mutha, P. K., Sainburg, R. L., & Haaland, K. Y. (2010). Coordination deficits in ideomotor apraxia during visually targeted reaching reflect impaired visuomotor transformations. *Neuropsychologia,* 48*,* 3855-3867.

Mutha, P. K., Sainburg, R. L., & Haaland, K. Y. (2011). Left parietal regions are critical for adaptive visuomotor control. *J Neurosci,* 31*,* 6972-6981.

Norman, D. A. (1981). Categorization of Action Slips. *Psychological Review,* 88*,* 1-15.

Norman, D. A. & Shallice, T. (1986). Attention to action: Willed and automatic control of behaviour. In Davidson R.J., G. E. Schwartz, & D. Shapiro (Eds.), *Consciousness* *and Self-regulation: Advances in Research and Theory* (vol. 4 ed., pp. 1-18). New York: Plenum.

Osiurak, F., Jarry, C., Allain, P., Aubin, G., Etcharry-Bouyx, F., Richard, I., Bernard, I., & Le, G. D. (2008). Unusual use of objects after unilateral brain damage. The technical reasoning model. *Cortex*.

Osiurak, F., Jarry, C., & Le Gall, D. (2011). Re-examining the gesture engram hypothesis. New perspectives on apraxia of tool use. *Neuropsychologia,* In Press, Corrected Proof.

Papagno, C., Della Sala, S., & Basso, A. (1993). Ideomotor apraxia without aphasia and aphasia without apraxia: the anatomical support for a double dissociation. *Journal of Neurology, Neurosurgery & Psychiatry,* 56*,* 286-289.

Poeck, K. (1982). The two types of motor apraxia. *Archives Italiennes de Biologie,* 120*,* 361-369.

Poizner, H., Clark, M. A., Merians, A. S., Macauley, B., Rothi, L. J. G., & Heilman, K. M. (1995). Joint coordination deficits in limb apraxia. *Brain,* 118*,* 227-242.

Randerath, J., Spijkers, W., Goldenberg, G., Li, Y., & Hermsdörfer, J. (2011). From Pantomime to actual use: how affordances can facilitate actual tool-use. *Neuropsychologia*.

Raymer, A. M. & Ochipa, C. (1997). Conceptual praxis. *Apraxia: The Neuropsychology Of Action,* 51-60.

Reason, J. T. (1984). Lapses of Attention in Everyday Life. In R.Parasuraman & D. R. Davies (Eds.), *Varieties of Attention* (pp. 515-549). Orlando. FL: Academic Press.

Rothi, L. J. G. & Heilman, K. M. (1997a). *Apraxia: The Neuropsychology of Action*. East Sussex (UK): Psychology Press.

Rothi, L. J. G. & Heilman, K. M. (1997b). Introduction to limb apraxia. In L.J.G.Rothi & K. M. Heilman (Eds.), *Apraxia: The Neuropsychology of Action* (pp. 1-6). East Sussex (UK): Psychology Press.

Rothi, L. J. G., Ochipa, C., & Heilman, K. M. (1991). A cognitive neuropsychological model of limb praxis. *Cognitive Neuropsychology,* 8 (6)*,* 443-458.

Rothi, L. J. G., Raymer, A. M., & Heilman, K. M. (1997). Limb praxis assessment. In L.J.G.Rothi & K. M. Heilman (Eds.), *Apraxia: The Neuropsychology of Action* (pp. 61-73). East Sussex (UK): Psychology Press.

Roy, E. A., Black, S. E., Barbour, K., Mcguiness, K., & Kalbfleisch, L. (1998). Pantomime and imitation of hand gestures following stroke. *Brain and Cognition,* 37*,* 127-129.

Roy, E. A., Black, S. E., Blair, N., & Dimeck, P. T. (1998). Analyses of deficits in gestural pantomime. *Journal of Clinical and Experimental Neuropsychology,* 20*,* 628-643.

Roy, E. A., Black, S. E., Winchester, T. R., & Barbour, K. L. (1996). Gestural imitation following stroke. *Brain and Cognition, 30,* 343-346.

Roy, E. A. & Hall, C. (1992). Limb apraxia: a process approach. In D.Elliott & L. Proteau (Eds.), *Vision and Motor Control* (pp. 261-282). Amsterdam: Elsevier.

Roy, E. A., Heath, M., Westwood, D., Schweizer, T. A., Dixon, M. J., Black, S. E., Kalbfleisch, L., Barbour, K., & Square, P. A. (2000). Task demands and limb apraxia in stroke. *Brain and Cognition, 44,* 253-279.

Roy, E. A., Square-Storer, P., Hoog, S., & Adams, S. (1991). Analysis of task demands in apraxia. *International Journal of Neuroscience, 56,* 177-186.

Ruh, N., Cooper, R. P., & Mareschal, D. A reinforcement model of sequential routine action. 65-70. 2005. Proceedings of International and Interdisciplinary Conference on Adaptive Knowledge Representation and Reasoning.

Ref Type: Conference Proceeding

Rumelhart, D. E., McClelland, J. L., & the PDP Research Group (2012). *Parallel Distributed Processing*. MIT Press.

Rumiati, R. I. & Humphreys, G. W. (1998). Recognition by action: dissociating visual and semantic routes to action in normal observers. *J.Exp.Psychol.Hum.Percept.Perform., 24,* 631-647.

Rumiati, R. I., Zanini, S., Vorano, L., & Shallice, T. (2001). A form of ideational apraxia as a delective deficit of contention scheduling. *Cogn Neuropsychol., 18,* 617-642.

Schaefer, S. Y., Haaland, K. Y., & Sainburg, R. L. (2007). Ipsilesional motor deficits following stroke reflect hemispheric specializations for movement control. *Brain, 130,* 2146-2158.

Schaefer, S. Y., Haaland, K. Y., & Sainburg, R. L. (2009a). Dissociation of initial trajectory and final position errors during visuomotor adaptation following unilateral stroke. *Brain Research, 1298,* 78-91.

Schaefer, S. Y., Haaland, K. Y., & Sainburg, R. L. (2009b). Hemispheric specialization and functional impact of ipsilesional deficits in movement coordination and accuracy. *Neuropsychologia, 47,* 2953-2966.

Schwartz, M. F. (1995). Re-examining the role of executive functions in routine action production. *Structure and Functions of the Human Prefrontal Cortex, 769,* 321-335.

Schwartz, M. F. (2006). The cognitive neuropsychology of everyday action and planning. *Cognitive Neuropsychology, 23,* 202-221.

Schwartz, M. F., Buxbaum, L. J., Montgomery, M. W., Fitzpatrick-DeSalme, E., Hart, T., Ferraro, M., Lee, S. S., & Coslett, H. B. (1999a). Naturalistic action production following right hemisphere stroke. *Neuropsychologia, 37,* 51-66.

Schwartz, M. F., Buxbaum, L. J., Montgomery, M. W., Fitzpatrick-DeSalme, E., Hart, T., Ferraro, M., Lee, S. S., & Coslett, H. B. (1999b). Naturalistic action production following right hemisphere stroke. *Neuropsychologia,* 37*,* 51-66.

Schwartz, M. F., Montgomery, M. W., Buxbaum, L. J., Lee, S. S., Carew, T. G., Coslett, H. B., Ferraro, M., Fitzpatrick-DeSalme, E., Hart, T., & Mayer, N. (1998a). Naturalistic action impairment in closed head injury. *Neuropsychology,* 12*,* 13-28.

Schwartz, M. F., Montgomery, M. W., Buxbaum, L. J., Lee, S. S., Carew, T. G., Coslett, H. B., Ferraro, M., Fitzpatrick-DeSalme, E., Hart, T., & Mayer, N. (1998b). Naturalistic action impairment in closed head injury. *Neuropsychology,* 12*,* 13-28.

Schwartz, M. F., Reed, E. S., Montgomery, M., Palmer, C., & Mayer, N. H. (1991). The Quantitative Description of Action Disorganization After Brain-Damage - A Case-Study. *Cognitive Neuropsychology,* 8*,* 381-414.

Schwartz, M. F., Segal, M., Veramonti, T., Ferraro, M., & Buxbaum, L. J. (2002). The naturalistic action test: a standardised assessment for everyday action impairment. *Neuropsychological Rehabilitation,* 12*,* 311-339.

Schwartz, M. F., Montgomery, M. W., Fitzpatrick-desalme, E. J., Ochipa, C., Coslett, H. B., & Mayer, N. H. (1995). Analysis of a disorder of everyday action. *Cognitive Neuropsychology,* 12*,* 863-892.

Shallice, T. (1988). *From Neuropsychology to Mental Structure*. Cambridge, UK: Cambridge University Press.

Sirigu, A., Duhamel, J. R., & Poncet, M. (1991). The role of sensorimotor experience in object recognition. A case of multimodal agnosia. *Brain,* 114 ( Pt 6)*,* 2555-2573.

Smania, N., Aglioti, S. M., Girardi, F., Tinazzi, M., Fiaschi, A., Cosentino, A., & Corato, E. (2006). Rehabilitation of limb apraxia improves daily life activities in patients with stroke. *Neurology,* 67*,* 2050-2052.

Soliveri, P., Piacentini, S., & Girotti, F. (2005). Limb apraxia in corticobasal degeneration and progressive supranuclear palsy. *Neurology,* 64*,* 448-453.

Spatt, J., Bak, T., Bozeat, S., Patterson, K., & Hodges, J. R. (2002). Apraxia, mechanical problem solving and semantic knowledge: contributions to object usage in corticobasal degeneration. *Journal of Neurology,* 249*,* 601-608.

Sunderland, A. & Shinner, C. (2007). Ideomotor apraxia and functional ability. *Cortex,* 43*,* 359-367.

Tanaka, Y., Iwasa, H., & Obayashi, T. (1990). Right hand agraphia and left hand apraxia following callosal damage in a right-hander. *Cortex,* 26*,* 665-671.

Tanaka, Y., Yoshida, A., Kawahata, N., Hashimoto, R., & Obayashi, T. (1996). Diagonistic dyspraxia. Clinical characteristics, responsible lesion and possible underlying mechanism. *Brain,* 119*,* 859-873.

Tessari, A. & Rumiati, R. I. (2004). The strategic control of multiple routes in imitation of actions. *J Exp Psychol.Hum.Percept.Perform., 30,* 1107-1116.

Trafton, J. G., Altmann, E. M., & Ratwani, R. M. (2011). A memory for goals model of sequence. *Cognitive Systems Research, 12,* 134-143.

Tretriluxana, J., Gordon, J., Fisher, B. E., & Winstein, C. J. (2009). Hemisphere specific impairments in reach-to-grasp control after stroke: effects of object size. *Neurorehabil.Neural Repair, 23,* 679-691.

Weiller, C., Willmes, K., Reiche, W., Thron, A., Isensee, C., Buell, U., & Ringelstein, E. B. (1993). The case of aphasia or neglect after striatocapsular infarction. *Brain, 116,* 1509-1525.

Westwood, D. A., Schweizer, T. A., Heath, M. D., Roy, E. A., Dixon, M. J., & Black, S. E. (2001). Transitive gesture production in apraxia: visual and nonvisual sensory contributions. *Brain and Cognition, 46,* 300-304.

Winstein, C. J. & Pohl, P. S. (1995). Effects of unilateral brain damage on the control of goal-directed hand movements. *Experimental Brain Research, 105,* 163-174.

Yelnik, A., Bonan, I., Debray, M., Lo, E., Gelbert, F., & Bussel, B. (1996). Changes in the execution of a complex manual task after ipsilateral ischemic cerebral hemispheric stroke. *Archives of Physical Medicine and Rehabilitation, 77,* 806-810.