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A NOVEL COMPUTER-AIDED NEUROLINGUISTIC APPROACH TO THE TREATMENT OF APHASIA

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Abstract

Aphasia is an impairment of language, affecting the production and/or comprehension of speech and the ability to read or write. Aphasia is always due to injury to the brain, most commonly from a stroke, particularly in older individuals. This paper presents a novel computer-aided training and rehabilitation approach to the therapy of aphasia. The system helps to treat and overcome the most severe consequences of this language disorder. The introduced novel methods and algorithms provide the implementation of self-adaptive training exercises to be used in different fields of the neurolinguistic therapy. They support all linguistic modalities and all important difficulty options used in the traditional face-to-face therapy. A software module was implemented based on the presented methods realizing a self-adaptive difficulty level control and multimedia exercises. The introduced system is embedded into a tele-rehabilitation framework, which offers a uniform interface for various telecare applications. The pilot study of the developed system is ongoing at several clinical sites in Germany.

Keywords: Aphasia, neurolinguistics, stroke, telecare, rehabilitation, speech therapy, multimedia.

1. Introduction

Computer-aided treatment, telecaring and telerehabilitation are all terms meaning cooperation of informatics and medicine. In case of illnesses that leave behind severe consequences or permanent damage and where the time required for a successful rehabilitation can be years, the day-to-day treatment activity is indispensable.

Employing telecommunications and informatics in healthcare makes possible for therapists to work with patients from remote locations. Comparing telecare with the traditional hospital treatment, the former can be more advantageous—when applicable—to the effect that the patient will not need to stay in a medical institute even for a long time, which he or she may feel unfamiliar. Individuals with acquired disabilities often suffer from the feeling that their illness threatens their independence because of losing more or less of the capabilities necessary for everyday life, thus they need the help of others.

In addition to providing a high standard of therapy, telecaring gives the patient a greater degree of independence and also enhances his or her self-esteem. Experience in the therapeutic field has shown that these play an extremely positive role in the rehabilitation process. A number of treatment types can be applicable at home—typically at post-traumatic or post-operative phase—, depending on numerous conditions, such as severity of the illness or the current condition of the patient and so on.

In most cases, the treatment series contain elements consisting of repetitive exercises, which the patient is instructed to execute on a daily basis in order to achieve an adequate improvement in his or her condition. This is a part of the rehabilitation program customized individually to the patient and needs a continuous monitoring and evaluation of the results after the treatments daily or weekly.

2. Preliminaries

Our study focused on a chronic illness called aphasia, which expressly needs a long-term rehabilitation program to defeat its most severe consequences. Combining a telecare environment with an appropriately designed aphasia treatment module can give the patient the possibility of a more intensive training in comparison with the traditional therapy led by a specialist only.

2.1. Medical Background of Aphasia

Aphasia is an acquired language disorder that affects a person's ability to communicate. It impairs the expression and understanding of language as well as reading and writing. Aphasia can occur suddenly, often the result of stroke, or it can occur over a period of time as a result of a brain tumor, causing damage to one or more of the language areas of the brain. Besides stroke, it can result from head injury, cerebral tumor, and other brain injuries.

Types of aphasia can be distinguished as follows:

- *Non-fluent aphasia (Broca's aphasia):* these people have suffered damage to the inferior frontal lobe of the dominant hemisphere. They speak in short, meaningful phrases that are produced with great effort. However, they are able to understand the speech of other people rather well.
- *Fluent aphasia (Wernicke's aphasia):* these people have suffered damage to the temporal lobe (towards the rear of the brain). They may speak in long sentences that have no meaning, add unnecessary words, or even create new words. These individuals also have great difficulty in understanding the speech of other people. They usually have no body weakness because their brain injury is not near the parts of the brain that control movement.
- People with *global aphasia* have suffered damage to extensive portions of the brain. They have severe communication difficulties and may be limited in their ability to speak or comprehend language.

- The symptoms also may be temporary; this type of aphasia is called *transient aphasia*. Transient aphasia refers to a communication problem that lasts only a few hours or days.

Thus far, no medicine, drugs, or surgery has been known to cure aphasia. Speech therapy is often provided to aphasic patients, but it does not guarantee a cure. Speech therapy is intended to help the patient utilize the remaining skills and learn complementary means of communication. Research and surgeries in the areas of brain repair and regeneration may provide for a partial cure in the near future. However, the speech therapy, especially the computer leaded exercise series and multimedia-based treatments are very important for a successful rehabilitation.

Currently there are no steps to prevent aphasia in the event of a stroke or head trauma. Some studies have cited several possible contributing factors to the onset of aphasia such as a high cholesterol level, but no conclusive results have been released. The condition is determined by the location and size of the area of damage to the brain [1].

2.2. *State-of-the-art Aphasia Therapy*

The so-called speech-language pathologist (SLP) works collaboratively with other rehabilitation and medical professionals (doctors, nurses, neuropsychologists, occupational and physical therapists, social workers etc.) to provide a comprehensive evaluation and treatment plan for the person with aphasia. Before the treatment series, the SLP completes an assessment of speech and language skills to determine the severity of the language deficit. This information is gathered through both structured observations and formal tests.

Speech therapy applied at the present time is usually a legacy face-to-face therapy, which means that the patient and the therapist sit facing each other and the patient gets several exercises that are intended to improve his or her communication skills. If the patient fails an exercise, the therapist changes the difficulty level, i.e. the patient continues with an easier exercise. In the case of aphasia, the patient is asked to pair pictures with written or spoken words (see *Fig. 1*), practice naming objects, complete words with some missing letters, find syllables in literal words, decide whether a word exists in the spoken language or not (pseudo-words) etc. The starting difficulty level of the exercises is determined by the expert, using the results of the preliminary test. According to the improvement of the patient's health, the complexity of the exercises will be increased, but in many cases the same scenario must be practised many times until some minor advance can be observed.

This process can be efficiently supported by computers, using multimedia features such as pictures, animations and audio sequences. People suffering from aphasia are usually limited in their moving, so a special input device is needed such as touch-screen (see *Fig. 2*), since precise pointing with a mouse or typing on a keyboard is nearly always impossible or very difficult for them.

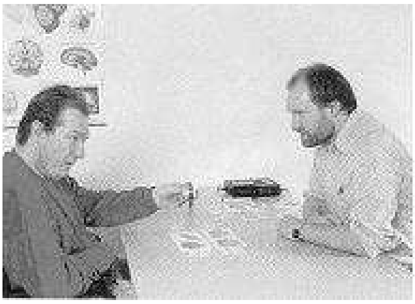

Fig. 1. Traditional face-to-face aphasia treatment. The therapist shows the patient some cards with pictures from which he is asked to select the appropriate one.

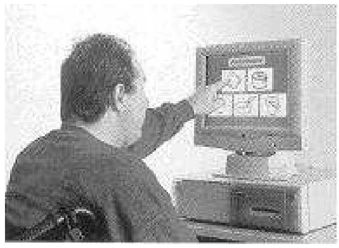

Fig. 2. An exercise from a computer-aided aphasia training. The patient selects a picture that belongs to the word on the top of the screen.

2.3. Goals of the Presented System

The purpose of a neurolinguistic software is to assist in treating of neurological patients suffering from aphasia, or more exactly, to supplement the legacy face-to-face therapy with the aid of computers and informatics. While the traditional clinical treatment series requires a neurologist or some kind of specialist, the neurolinguistic software can independently help to bring back the patient to a normal life, with regular but not constant supervision of the expert. Apart from the fact that such a system can make the therapists everyday work easier, it also offers the possibility of independent treatment at the patient's home. This means that the therapy of aphasia can be made successfully without the constant presence of a neurologist or other kind of expert.

Examining many existing therapeutic systems on the market, we can notice that most of them show some major deficiencies, which can arise as natural expectations during the usage. Some issues that were noticed by practising speech-language pathologists concerning other softwares are as follows.

- In many cases there is no possibility of practising exercises by the patient unaided. This results from—among others—that the user interface of the software is not clear and unambiguous, it is hard to use; the exercises lack for randomization; there are no limitations on the duration of a training; sometimes error messages appear and other events arise that can seriously confuse the patients and prevent them to go on with the exercises.
- The diversity of the exercises is sometimes unsatisfactory; in some cases they are constituted with a rather simple architecture, while many training types can be realized only with difficulties without the aid of computers.
- The arrangement of the exercises also lacks for randomization, which can

lead to a learning effect as a harmful consequence; this is inconsistent with the fundamentals of the aphasia therapy.

- At certain systems there is no separate dictionary database; the exercises and their contents are fixed.
- Sometimes there is no hierarchical structure of the difficulty levels, which can make more difficult or even prevent the systematic training.

1) The tele-care framework system: In order to meet the requirements of a tele-care system, the software has been embedded into a framework, which provides a unified interface to several software modules (plugins). These plugins use the same database where all the information is stored about the patients, for this reason, one patient may obtain many different kind of treatment simultanously. The patient can begin to use the system by logging in with an electronic card similar to telephone cards (smart card), then the framework retrieves the current prescriptions for that day via dial-up networking besides other important data. After the patient finished with the exercises, the system sends back the results to the server for further processing and storing.

Requirements for an aphasia treatment software: The general requirements and expectations for the presented system can be outlined as follows:

- *Functionality*: The system shall give the possibility of independent training series, i.e. it will be used without supervision at the patient's home. For this reason, it is particularly important to provide a user interface which is easy to handle, giving the possibly least verbal and written instructions for the patient—this is where they may have serious weaknesses. It is also of great importance to mention the reliability about the functionality to the effect that no software malfunctions or error messages may appear because most of the patients cannot interpret and manage them.
- *Quality*: Concerning the linguistic content of the software, the structure of the exercises shall reflect the issues of the recent researches on neuro-linguistics and other related fields of research. Nevertheless, in formal and technical respects, the controllability, the components that form together the exercises (database, randomizing, expandability) and the stability of the system have all to meet the special requirements set up by the independent training of speech defective people.
- *Usage*: The software shall be prepared for clinical, ambulant and home usage. Therefore, the user interface shall follow the latest design trends considering particularly the issues of software ergonomics. The time required for learning the usage of the software shall be the least possible; the inexperienced user can get stuck in a badly developed user interface.

These requirements were all taken into consideration during the development of the system.

3. Methods

3.1. Basic Concept

The main concept of the system is the fact that the activity of the more or less injured language center of the brain can be improved by executing a large amount of simple, language-specific exercises. These trainings stimulate the language area of the brain, helping it to utilize its intact regions by re-learning the missing skills. The general structure of an exercise series can be outlined as follows:

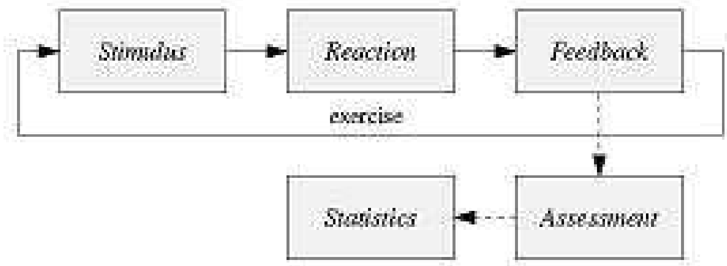

Fig. 3. Elements of an exercise series. The continuous feedback ensures the variability of the difficulty level, while the assessment module helps the therapist plan the future treatment sessions.

The exercise cycle repeats as many times as needed during a treatment session. That is, the patient gets a stimulus on which he or she reacts somehow, then an indication will be delivered by the software whether the response is correct or not. The loop ends when certain conditions are satisfied (success ratio hits a given limit, time for the exercise is out etc.). During an exercise, the first step is that the patient is shown a stimulus (or combination of stimuli), which can be the following:

- *Picture* (color photograph of an item, such as things, vegetables, fruits, consumer goods, furniture etc.)
- *Audio record* (pronounced words)
- *Lexeme* (literal image of a word)

The patient then responds to the stimulus (stimuli), what means that he or she tries to select the correct answer by tapping an object on the touch-screen. Following the patient's reaction, the software shows whether the response was correct or not and in case of error, it reveals the correct answer. According to the success/failure ratio of the patient, the software adaptively increases or decreases the difficulty level of the exercises during a sequence so that the treatment can be successful.

Further analysis and comparison with other patients is possible by using the assessment and statistics modules that are tightly integrated with the framework system. After each treatment session the results will be transmitted to the care center, where all data are archived and stored for future processing. The assessment module allows the therapist to follow up the changes in the patient's state during a long period, what can be useful when planning and assembling a new treatment series. With the help of the statistics module, trends can be discovered among cases.

Summarized, to develop the neuro-linguistic therapeutic software system, the following tasks are to be completed:

- Creating a data representation and assignment of the linguistic units (grapheme, syllable, word, sentence);
- developing algorithms which determine the quantitative relation between the linguistic units;
- maintenance and automatic generation of the computed measures on database changes;
- developing a multimedia GUI with multiple modalities and stimuli for the neuro-linguistic exercises which uses the special vocabulary database;
- algorithms for difficulty adaptation according to the current condition of the patient; assessment and statistics module for further analysis in order to reveal improvements or impairments.

The further sections focus only on the theoretical background of the phonetic and semantic distraction, the user interface and the engine of the exercises are not discussed in this paper.

3.2. Difficulty Metrics Used in the Exercises

It results from the aphasic symptoms that the main difficulty for an aphasic patient is to discriminate between words with similar meaning or between those sound alike. It follows from the foregoing that if we intend to create a general algorithm which adaptively modifies the difficulty according to the patient's skills, it will require the calculation of measures which characterize the distance between two words.

The first one called *semantic distance* is a numeric grading which gives the similarity between words. In order to make possible such a computation, each word is associated with a so-called *generic term* (e.g. animals, plants, fruits, furniture, flatware, mammals etc.), which is actually an attribute of the word. The generic terms are arranged into a tree-structure allowing to create word-families. Two words associated to the same generic term or to those being on the same level in the tree have similar meaning. This user-adjustable database is essential because it is obvious that no algorithm can determine any semantical relationship between words of a human language without supplementary information.

The second one called *phonetic distance* is a numeric measure too, which describes the similarity between two words in sonority. The phonetic distance is computed using the so-called phonetic transcription of words, what means that all words have such an equivalent which uses standardized symbols to describe the sound of a word.

1) Computation of semantic distance: As mentioned earlier, the base of semantic distance computation is a tree of terms. This tree is such a data structure, where moving toward the root we can find terms with even more general meaning, while near the leaves there are specialized ones. Walking along a branch of the tree, we can find, for example, the following chain of terms: [*creatures→ animals→ birds→ songbird*] or [*objects→ manufactures→ furnishings→ furniture*] etc.

In the examples, we started the traverse from the root of the tree. The semantic tree has two entry types: simple abstract or more special terms and references to another dictionary entries. That is, some items in the vocabulary may serve also as terms in the tree. Obviously, a word cannot be the semantic grading of itself. In the linguistic database each item is assigned to an element from the tree, so the semantic distance of two words will be characterized by the relation between the terms associated to them. Basically, the length of the path that leads to the common "ancestor" of the term-pair, walking toward the root (e.g. the ancestor of both *birds* and *mammals* is *animals*), will determine a measure for this relation.

Opposing to the phonetic distance where the value of the relation is in the near of zero at very similar sounding words, we defined the semantic distance more likely a grade of semantic relationship. Therefore, less value means more distance in meaning, while the value range is limited by the depth of the concept tree. The general formula of the semantic distance is the following:

$$R_{Sem} = R_{max} - S = R_{\max} - (L_h - M) \tag{1}$$

where $R_{\max}$ denotes the greatest value of the relationship, S denotes the number of steps leading to the common ancestor of the terms assigned to the word-pair. S is the difference of L_h, the maximum length of the hash-code of the terms ordered to the words, and M, which is the position (level) of the 'meeting point' of the terms:

$$\begin{aligned} M &= L_{h_c} \\ H_c \in H \quad (h_c \mapsto h_1) &\wedge (h_c \mapsto h_2) \end{aligned} \tag{2}$$

Here the relation $\mapsto$ means 'beginning with': the Hash-code of both words contains h_c as a substring from the beginning of the codes. Actually, L_h = max (L_{h1}, L_{h2}), where L_{h1} andL_{h2} denote the length of the Hash-codes of the two concepts assigned to the words, respectively.

2) Computation of phonetic distance: To determine the phonetic distance, it is very important to unambiguously identify the various phonemes from the words. Once they are extracted correctly from the lexemes, the measure of distance can be obtained by analysing these phonemes of the two words to be compared and performing some computation on them. It leads to a single real number which will characterize the phonetic distance. The less this value, the more closeness in sonority can be measured between the words. The so-called *syntagmatic phonetic*

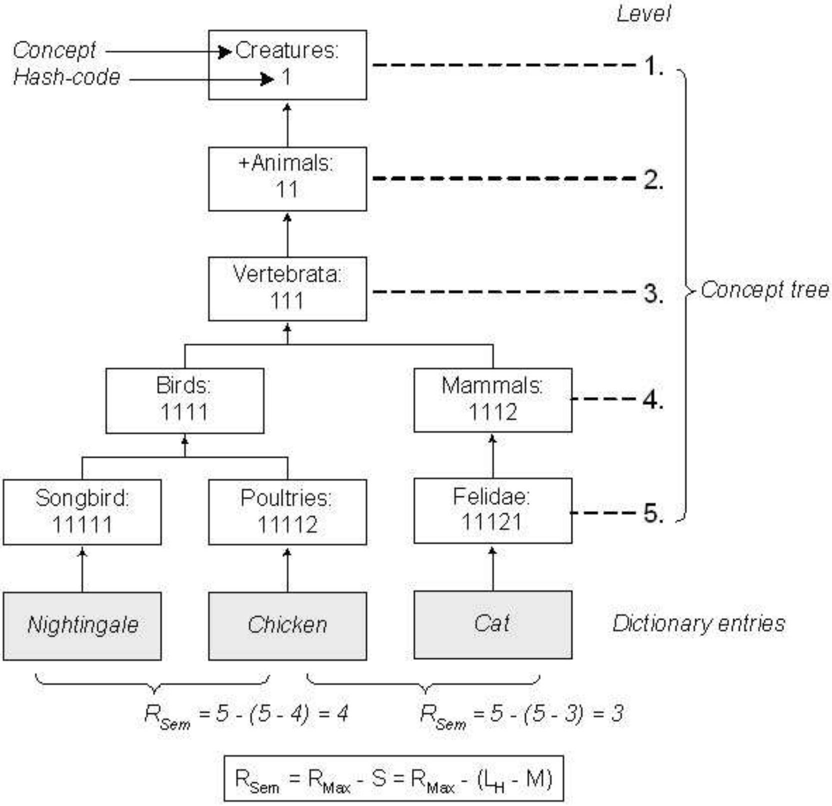

Fig. 4. Part of an example semantic tree with hash codes. The dictionary entries are leaves on the tree; the entry 'animals' is a root for the search for semantic distraction words.

distance (SPD) can be computed using the following formula:

$$SPD = \frac{c_1 S + c_2 E + c_3 R}{W_L + a} + A + c_4 M \tag{3}$$

$$E = WL - WS, \quad S = \sum PPD, \quad R = K - r \quad M = Syl_L - Syl_S \tag{4}$$

The meaning of the variables is as follows:

The *paradigmatic phonetic distance* (PPD) is defined between two phonemes and constitutes of a sum of measures which characterize the formation of a given phoneme. Every vowel and consonant has such a set of values—the so-called *articulatory-perceptual descriptor* (APD)—referring to anatomical properties that have an influence on the audible similarity or unconformity of two (spoken) words

Table 1. Variables and their meanings in the above formulas

Notation	Description
W_L, W_S	Number of phonemes in the longer and the shorter word, respectively.
E	Number of elisions (addictions), that is, difference of word lengths.
S	Substitution value, sum of the so-called *paradigmatic phonetic distance* computed on the corresponding phoneme pairs.
K	Number of identical phonemes in the words.
r	Number of identical phonemes which also stand in the same position in the words.
R	Number of identical phonemes violating the order (complementary of r).
M	Difference of number of syllables.
Syl_L, Syl_S	Number of syllables in the longer and the shorter word, respectively.
A	Constant which has different value when the first phonemes of the words match.
c_1, c_2, c_3, c_4, a	Weights which are determined using a try method. The goal was that for the obviously similar words the formula should give the lowest result.

(see *Fig. 5*). We have defined three forms of PPD, according to the phoneme types being in comparison.

$$PPD_C(p_1, p_2) = \sum_{a_c \in A_c} |APD(a_c, p_1) - APD(a_c, p_2)| \tag{5}$$

$$A_c = \{\text{Friction, Opening, Nasality, Articulation, Phonation}\}$$

$$PPD_V(p_1, p_2) = \sum_{a_v \in A_v} |APD(a_v, p_1) - APD(a_v, p_2)| \tag{6}$$

A_v = {Height, Location}

$$PPD(p_1^c, p_2^v) = PPD(p_1^v, p_2^c) = C_{cv} \tag{7}$$

In the formulas above the lower index of the PPD means consonant or vowel, referring to the fact that different attribute sets are employed in the computation. The APD function takes two parameters: the linguistic attribute a_c or a_v and the phoneme $p_{1,2}$, so it defines a two-dimensional array of real numbers. These values—projected on a given attribute—acceptably reflect the "weight" of a phoneme. For example, the friction value of the phoneme 's' is set to 0.4, while the same for 'v' is 0.2 and for 'b' is 0.

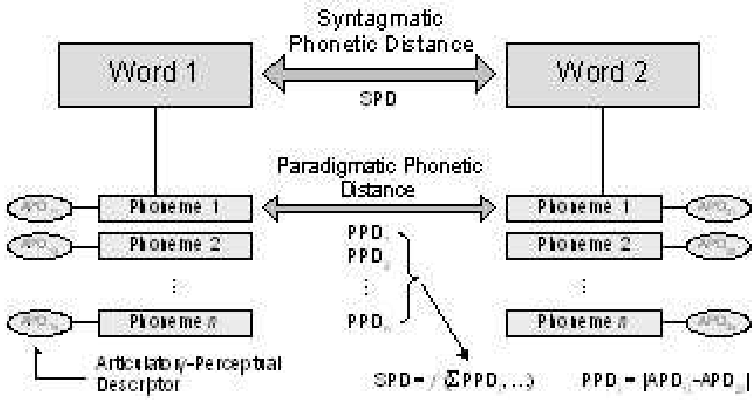

Fig. 5. Relationship between the linguistic terms SPD, PPD and APD. In the figure both words have the same number of phonemes, for simplicity.

We decided to consider the PPD between different types of phonemes as constant since no reasonable computation is available because of the different property sets assigned to the consonants and the vowels. Nevertheless, the audible difference in general between consonants and vowels gives grounds for using a value of 0.6 to reflect their impact on the SPD.

3.3. Distraction Sets

Generation of the semantic and phonetic distraction set of a given word is based on the computation of the distance between the word and (almost) all other entries in the dictionary.

- The *phonetic distraction set* of a word consists of entries with distance below a given limit, that is,

$$D_P = \{w \in V \quad SPD(w, w_i) \leq SPD_{\max}\} \tag{8}$$

where V denotes the vocabulary. The phonetic distance range is then partitioned into smaller sections (limited by $SPD_1, SPD_2, \ldots, SPD_n \in \Re$) which will determine the difficulty grades—actually this means a conversion between phonetic distance and difficulty grade, ranging from 1 to $DG^P_{\max} \in \mathrm{N}$.

- The *semantic distraction set* of a word consists of a given subset of dictionary entries; the computation of semantic distance is performed only on a limited set of words, formally

$$D_S = \{w \in V \quad h(r(w, w_i)) \mapsto h(w)\} \tag{9}$$

here $h(.)$ gives the hash-code of a term associated with a given word as a character string, $r(.)$ obtains the term which is the nearest ancestor of the meeting point of the terms assigned to the word-pair and annotated as a "limiter" (See Fig. 4., the name of the limiter concept begins with a plus sign) and the hash-code of the distraction should begin with that of the limiter concept. In other words, the search for the semantic distraction words does not involve entries with an assigned concept belonging to another branch of the tree. The difficulty grade is ranging from 1 ("neutral" distraction) to $DG^S_{\max} \in \mathrm{N}$.

In the case of phonetic distraction, the relation between the distance and the difficulty grade is inverse: words with phonetic distance of 0 to SPD_1 will be graded as difficulty level of $DG^P_{\max}$; distance between SPD_1 and SPD_2 will be assigned to $DG^P_{\max} - 1$, etc.

At the semantic distractions, the assignment of difficulty grade and distance is straight: R_{max} will be assigned to$DG^S_{\max}$,$R_{max} - 1$ will be assigned to$DG^S_{\max} - 1$ etc.

Words with distance of $R_{Sem} = 1$ from the current word are considered as neutral distractors, so they will not be stored in the database.

3.4. Linguistic Database

The linguistic database used by the therapeutic system contains the dictionary which constitutes the vocabulary of the exercises along with the tree of concepts whose items are assigned to each entry in the dictionary. Since the generation of semantic and phonetic distractors may take relatively long time, and in addition, this time is hard to estimate, the conception at the database design was that the system should use such a database where the derived information is wired-in, i.e. the distractors are stored within the database at every word. Only this approach can guarantee a real-time operation which is a fundamental requirement for the system. Therefore, two databases are used: a *dynamic* one which can be edited by a database tool and a *static* one that contains all information for the exercises including the distractors.

4. Discussion and Conclusions

Applying the terms and technical requirements defined by experts we have implemented the algorithms that automatically produce the semantic and phonetic distractions along with a utility which processes, filters and stores them in a suitable database. A multimedia graphical user interface has also been developed which uses the generated dictionary at the exercise series.

The present system is designed for the german language area; the phonetic transcriptions of the vocabulary entries come from the CELEX database, what enables the adaptation of the software for Dutch or English languages as well. After the experiments, the algorithm that computes the phonetic distance yields an adequate quality of result; in practice, testing with a ca. 1800-word long dictionary assorted by an expert, the program produces a satisfactory amount of phonetic distractions for each entry. In some cases, resulting from a small number of exceptions and sounding similarities that are difficult to express with simple algorithms, there may be incorrectly detected near words in the distraction sets, but considering the practical size of the dictionary, these are—agreeing with the experts—of minor importance.

The semantic distraction generator has no parameters based on empirical values, it works entirely using the previously created category-tree which is assigned to the dictionary entries. It can be considered that this completely meets the requirements for semantic distractions. The pilot phase of the system is going on, it is applied at several clinics in Germany—along with the Rehabilitation Clinic of Herzogenaurach—as a new treatment type. The neurologist and logopedic experts who gave their professional support are also satisfied with the product; further development has possibilities after a successful clinical practice. There are, of course, many possibilites of additional functions to be implemented, such as

- employing of higher grammatical modalities, i.e. compound words, expressions, sentences;
- handwriting recognition for exercises intended to improve writing skills;
- voice and speech recognition for exercises to improve fluency in speech.

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