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An Activity-Theoretic Approach to Intention Estimation

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Abstract: Traditional powered wheelchair control is especially for severely disabled people cognitively and physically demanding due to the high number of input commands necessary. An intention estimation behaviour, which considers the cognitive processes of the actor, is discussed as one way in order to significantly reduce the number of required input commands. For this purpose, a continuum of, from other researchers discussed modes of human behaviour is introduced as well as cognitive processes underlying this continuum of human behaviour. A study conducted with wheelchair users confirms major assumptions of the theory and allows drawing implications for realizing an intention estimation behavior considering the cognitive processes of the actors.

1. MOTIVATION AND STATE OF THE ART

Intention estimation is an important means to improve the usability of technology assisting especially elderly or people with disabilities. Assistive devices and particularly (powered) wheelchairs aim at simplifying everyday issues, in enabling the target population to live as far as possible independently, and in enhancing the quality of life of the people in need. However, as evaluations of such assistive technologies demonstrate (see e.g., Bailey & DeFelice, 1991; Fehr, Langbein & Skaar, 2000) currently commercially available powered wheelchairs imply serious drawbacks: Case studies (e.g., Bailey et al., 1991) report of individuals with high-level spinal cord injuries, multiple sclerosis or brain injuries, who have spent months and even years learning how to control a powered wheelchair. These case studies have been supported by the results of surveys of clinicians about the difficulties their patients, who receive a special training about how to control a powered wheelchair, face (Fehr, Langbein, & Skaar, 2000):

- For 9-10% of these patients it is very difficult to use a powered wheelchair in their everyday life.
- For 40% it is hardly possible to accomplish special manoeuvring tasks.

Despite these troubles, some patients, which are nearly as many as those receiving training, are not enrolled in the training courses as they are not expected to be able to control a powered wheelchair successfully even with training due to lacking motor skills, strengths or visual acuity.

These problems can be expected to be even of greater relevance for people not being able to control their powered wheelchair with traditional control devices such as joysticks and require so called speciality controls such as sip-puff devices or chin controls. These speciality controls only allow a very limited set of input commands. This is why even simple behaviours (such as driving around a table) can only be achieved with many input commands (e.g., driving straight ahead, stopping, changing the mode of the wheelchair, driving to the right, stopping, changing the mode of the wheelchair, driving straight, etc.). Symptoms of fatigue, high cognitive load (especially for people with cognitive impairments) and long training periods are the result.

Hence, in order to make assistive devices more usable, the number of input commands needs to be reduced in an intuitive way. One such solution is intention estimation. If the technical system were able to “foresee” its user’s behavioural intentions, it could provide much better targeted support (e.g., driving the person automatically around the table) and, as such, significantly reduce the number of input commands required by its user.

Approaches of intention estimation to increase the usability with especially powered wheelchair control can be classified depending on the level of support they offer (for a more detailed review of existing approaches, see Bartolein, Wagner, Jipp, & Badreddin, 2007): First, methods, which were originally developed in the field of robotics, were adapted to meet the special requirements of assistive technology and implemented on (semi-)autonomous wheelchairs. These methods only provide intention estimation on a very low level. For example, Bell, Borenstein, Levine, Koren, and Jaros (1994) realized a collision avoidance behaviour on a powered wheelchair. Other researchers aimed at simplifying navigation by implementing basic behaviours such as wall following or door passage (see e.g., Lankenau & Röfer, 2000). Second, higher level support realized intention estimation on the basis of probabilistic procedures. For example, Demeester, Nuttin, Vanhoydonck and Van Brussel (2003) extrapolated the route indicated by the user’s past input and compared it with potentially requested routes based on the environment.

These already existing approaches exhibit the following disadvantages:

- Especially the lower level support only facilitates navigation in special situations (such as following a wall) but do not provide comprehensive support beyond these special situations.

- The higher levels of intention estimation only use low-level information to reason about the possible behavioural goal position of the user, but ignore ongoing cognitive processes of the user, which could give valuable input for the intention estimation. This might reduce the transferability of the probabilistic approaches to unknown environments. Hence, in these unknown environments, an appropriate level of support might not be available.

2. PROBLEM STATEMENT

Due to the above described disadvantages of existing approaches, it is expected that they do not comprehensively tackle the described problems with traditional powered wheelchair control and do not provide considerable means for significantly and meaningfully easing traditional wheelchair control in everyday life. Correspondingly, this research aims at analyzing human behaviour in order to provide the necessary insights allowing for an intention estimation behaviour considering the cognitive processes of the user.

3. SOLUTION APPROACH

In order to tackle the problem, a three-step procedure has been taken. First, a theoretical framework of human behaviour based on activity theory (see Section 3.1) is developed and second, major hypothesis of this theory have been tested empirically (see Section 3.2). Last, practical implications about the results in respect to intention estimation are provided (see Section 3.3).

3.1 Theoretical Foundations

Various researchers have defined different modes of human behaviour.

For example, Gibson (1966) distinguished between exploratory behaviour and performatory activities: *Performatory activities* are realizations of affordances provided by the environment. These affordances are environmental action possibilities (Gibson, 1979) and reflect the actions the combination of mediums, surfaces and substances in the surrounding offer. For example, a phone owns the affordance "making a phone call". *Exploratory behaviour* refers to activities which are aimed at actively seeking further information about the surrounding. For example, a hand free to explore an unknown object better allows for discrimination between a similar object as is possible with a hand that is constrained.

Another dichotomy between different modes of human behaviour has been described by Suchman (1987). She distinguished between instrumental *goal directed activities* and *creative, expressive actions*. In parallel to Gibson (1966), Suchman (1987) argues that, which behaviour is activated, depends on the familiarity of the actor with the current situation.

Other researchers have stressed that such a dichotomy is not sufficient to describe human behaviour. A group of Russian psychologists founded activity theory and its basic component stating that the human mind can only be understood in the context of meaningful, goal-oriented, and socially determined interaction between the actors and their environment (Leontyev, 1978). Leontyev (1978; see also Kuutti, 1996) distinguishes between different types of meaningful interactions:

- *Activities* are reactions on human motives, which explain why something takes place.
- *Actions* are conscious components of activities guided by a goal.
- *Operations* explain how actions are implemented to achieve the goals.

The interaction with the environment is subject to chance depending on practice (Kuutti, 1996): With practice, an activity looses its motive and turns into an action; an action becomes an operation as the planning and decision component fades. The execution of operations becomes more fluent and the consciousness of the operations fades. For example, initially the activity "playing piano" satisfies the motive of achievement. This activity is comprised of various actions, e.g. "buying new music sheets". Such an action is, again, composed of various operations, e.g., "driving to the store". With practice and familiarity, "driving to the store" will turn automatic, it is no longer necessary to plan the route to the store, because the actor has driven it lots of times. The original action of "buying new music sheets" turns into an operation, while the activity "playing piano" looses its motive and turns into an action.

These researchers highlight the importance that the mode of human behaviour depends on the familiarity of the action to take place. However, the definition of underlying cognitive processes has been neglected so far. On the basis of the work of Rasmussen (1983) and Jipp, Bartolein, and Badreddin (2007) it is argued that specific cognitive processes underlie the continuum of modes of human behaviour:

While initially, when confronted with a new environment, the visual information available does not specify an affordance (see also Gibson, 1979). Hence, no patterns of movement are at hand to satisfy a motive and exploratory or creative behaviour is executed, which will give the actor valuable information about the environment. The execution of such expressive behaviour provides the actor with information, which is used to complement visual and/or auditory information. This information about the environment is used to build an internal model of the environment. Based on this internal representation, ways of satisfying the motive can be worked out. The effects of the operations can be simulated mentally and the supposedly most promising one realised. The feedback from the environment and the achieved result(s) will again allow further elaborating the internal representation of the situation. The requirement to process information is at the maximum level. With continuing exposure and experience in the environment the motive will step into the background and the focus will be put on defining the optimal way and combination of carrying out the operations. Taken together, the operations still form an action. With further practice, the optimal way of achieving the goal is specified and the patterns of movement worked out. A specific goal is no longer formulated. What originally composed the activity is now an operation, which will, with further practice even loose the still required consciousness.

Summarising, researchers (e.g., Gibson, 1966; Suchman, 1987; Kuutti, 1996) have differentiated various modes of human behaviour. However, these modes are not considered as distinct categories (such as stressed by Gibson, 1966 or Suchman, 1987), but as continuous. The crossovers from one mode to the next or the transition from activities to operations are determined by the person's familiarity in the situation. Furthermore, cognitive processes and functions underlying the different modes of human behaviour have been defined: These cognitive processes first refer to building an internal representation of the external environment, which will be used for reasoning and mental simulation, and second to using feedback about conducted operations in order to define an optimal way of satisfying the relevant activity.

3.2. Conducted Study and Results

The above described theory comprises two major areas: First, it states that there is a crossover from the various modes of behaviours proposed by various researchers. Second, a reasoning of the cognitive processes behind these different modes of human behaviour has also been introduced. In order to test the major assumptions underlying the crossover and the cognitive processes at hand, a study has been conducted, which is described in the following.

3.2.1. Research Questions and Hypotheses

The continuum between the different modes of human behaviour can – on the basis of the underlying cognitive processes – be described in three phases:

In a first phase, a cognitive representation of the situation is built. For this purpose, sensory information is complemented with haptic information from executing creative actions or exploratory behaviour. Valuable feedback about the environment's features is derived. This exploratory behaviour manifests itself in the number of task-irrelevant operations, i.e., the number of operations which are not related to achieving the goal in question. If the exploratory behaviour supports the formation of an internal representation, the number of exploratory behaviour should decrease in relation to the total number of operations performed to achieve the goal. Due to the informational value of the task-irrelevant operations, it is also expected that not only their number decreases with increasing familiarity of the environment. The following two hypotheses result:

- The total number of task-irrelevant operations in relation to the total number of operations decreases linearly with the number of tasks performed (H_1).
- The average duration of the task-irrelevant operations in relation to the average duration of the total number of operations performed decreases linearly with the number of practice trials (H_2).

In a second phase, it is expected that feedback from the executed operations is used to complement the internal representation and allows working out an optimal realization of the required operations. For this purpose, changes at two levels of abstraction occur: First, the way operations are executed changes, which can be measured based on the speed with which they are carried out. This is why it is expected that the average duration of an operation decreases with the number of practice trials performed. Second, different combinations of operations and their impact on successful performance are tested by the actors. Hence, the number of strategic shifts is expected to change. As both processes are only initiated after the internal representation is at least to some extent worked out. The change is expected to follow an inverted u-shaped course. The following two hypotheses result:

- The average duration of an operation is expected to decrease linearly with the number of practice trials performed (H_3).
- The number of strategic shifts is expected to decrease with the familiarity of the tasks (H_4).

After the cognitive representation has been built and promising actions have been worked out on the basis of mental simulation, the operations, which were initially actions or even activities, are grouped. Hence, the number of actions performed decreases linearly with the familiarity of the situation:

- The number of actions performed is expected to decrease with the number of practice trials (H_5).

3.2.2. Course of the Study and Description of the Sample

In order to test these five hypotheses, a study has been conducted at the vocational college at the Evangelische Stiftung Volmarstein (www.esv.de) in Wetter, Germany. Thirteen participants volunteered in taking part in this study. The sample size allowed for reliably detecting a large effect (i.e., $f^2 > 0.25$), if the hypothesized effects were there according to the conducted power analysis and a priori sample size estimation (Cohen, 1988). These participants were enrolled between one and four years in their vocational training, they were on average 23.38 years old, the majority was male and right-handed. All participants used a wheelchair for an average of 17.43 years because of differing disabilities: The majority of the participants received the diagnosis spasticity, others suffered from spina bifida, from dysmelia and from incomplete paralysis.

The participants conducted gardening tasks. Due to their disability, the participants could not enrol in the according professional formation, so that it was assumed that the participants were neither familiar with their environment nor with the actions they had to perform in order to achieve the goals. The task, the participants had to fulfil, was to lead a little market garden and work out the wishes of the customers. Four customers were simulated: The first one requested sowed sunflower seeds, the second set in flowering seedlings, the third set in foliage seedlings and the last one sowed ransom seeds. For sowing seeds and setting in seedlings different operations were necessary. In order to sow in seeds, the following steps were required (see also Jipp, Bartolein, & Badreddin, 2006):

- The pots, in which the seeds had to be sowed in, needed to be placed in an appropriate seed box.
- Soil had to be filled into the pots and loosed.
- A hole had to be made into the soil in the pots.
- One seed had to be filled in each hole.
- If the seeds were light germinators (as indicated by the customer wish), the holes had to be covered by wettish newspaper.

- If the seeds were dark germinators (indicated as well on the customer wish), the holes had to be covered with a small layer of soil.
- The pots had to be watered, whereas the water had to be prepared in order to have the ideal temperature and acid value (both were given in the instructions).

In order to set in the seedlings, the following steps had to be executed:

- An appropriate pot had to be chosen and filled half with loosened soil.
- The seedlings had to be put into the pot.
- The right fertilizer had to be chosen and the rest of the pot filled with alternating layers of it and of soil.
- The plant had to be moistened with water with a temperature of 25°C and with an acid value between five and six.

Everything the participants required in order to successfully execute the customer wishes was distributed in their environment. Fig. 1, for example, shows parts of the environment, in which the study took place.

Fig. 1. Picture of one of the tables on which e.g., the seed box, the soil, the seedlings, etc. were placed.

3.2.3. Data Analysis

In order to test the hypotheses stated in Section 3.2.1, videos of the participants executing the tasks, i.e., the four customer wishes, were transliterated in a first step. For this purpose, a set of possible operations was defined (e.g., picking up soil, moving soil to pot 1, pouring soil in pot 1, etc.). The starting and ending points of each operation for each participant and each task were defined. Further, all possible operations were classified according to whether they were relevant (e.g., pouring water in pot 1) and irrelevant (e.g., covering pots with soil, if the pot had to be covered with wettish newspaper) for achieving the major goal of that specific task. By subtracting the ending and starting times of each operation, the durations of each operation were calculated. On the basis of these data (i.e., definition of operation, definition of its relevance and duration per task and per participant), the following variables were calculated:

- total number of task-relevant operations per task and per participant
- total number of operation per task and per participant
- duration of all task-irrelevant operations per task and per participant
- duration of the total number of operations per task and per participant

On their basis, the variables relevant for analysing the hypotheses were derived:

- The total number of task-relevant operations per task and participant was divided by the total number of operations per task and participant. This variable (NIO) was used to analyse H_1.
- The duration of all task-irrelevant operations per task and per participant was divided by the total duration of all operations per task and participant. The resulting average duration of a task-irrelevant operation per task and participant was divided by the average duration of any operation per task and participant (i.e., the total duration of all operations per task and per participant divided by the total number of operations per task and per operation). The resulting variable DIO was used to calculate H_2.
- The total duration of all operations per task and per participant were divided by the total number of operations per task and per participant. The resulting average duration of an operation (DO) was used to analyse H_3.

To derive how often the participants changed their strategy in achieving the task, the order of operations performed was analysed for each task and each participant. The number of strategic shifts (NST) was calculated by counting the number of times, each participant changed the order he/she executed the operations and/or actions. This variable was used to calculate H_4.

The number of actions (NA), the variable relevant for analysing H_5, was calculated by counting the number of grouped operations, which were not interrupted by periods of uncertainty and/or periods of rest for each task and each participant. A period of uncertainty was defined as comprising insecure behaviour including e.g., the operations "routing", "reading instructions", or "asking for help". A rest period was defined as an operation "break", i.e., when no operation was performed.

The resulting variables NIO, DIO, DO, NST, and NA for each task and each participant were fed into five general linear model analyses with repeated measurements as dependent variables. In order to control further variance, two aggregates of controlling variables were used including age, sex, handedness, type of disability, last school leaving certificate, field of vocational training, interest and experience in agriculture as well as the number of years, the wheelchair has been required. In case the results indicated that one or both aggregates do not account for a significant proportion of the variance of the dependent variables, they were excluded. The results of these general linear model analyses and, more specifically, the used test statistic and its degrees of freedom, the probability p that the effect is not there and the effect size f^2 are given in Table 1. The effect sizes are further classified according to their size on the basis of Cohen (1988).

The results given in Table 1 indicate three highly significant effects, which are large according to Cohen's (1988) classification:

- First, H_1 can be confirmed (see also Jipp, 2007): The total number of task-irrelevant operations in relation to the total number of operations changes while executing the customer requirements. The conducted polynominal tests further confirm a linear effect ($F(1, 10) = 10.74$ with $p < 0.01$), which is depicted in Fig. 2.
- Second, H_3 also reveals a highly significant effect: The average duration of an operation decreases in the course of the four trials performed. Again, the polynominal tests confirm the linear shape of the variable overall practice trials ($F(1, 10) = 16.06$, $p = 0.00$), which the scatterplot with the linear smoother given in Fig. 2 verifies.
- Third, the number of strategic changes varies significantly overall practice trials (as hypothesized in H_4). The variable demonstrates an inverted u-shaped course, as can be seen in Fig. 2. This shape was also confirmed by the significant result of the quadratic term of the polynominal tests ($F(1, 10) = 8.43$, $p = 0.02$).

The results further revealed one effect, which is significant with $\alpha < 0.05$., i.e., the number of actions performed while practicing. In the course of the execution of the four customer requirements, the number of actions performed decreases linearly (see Fig. 3 and Jipp, 2007). The linear decline is confirmed by the conducted polynominal tests, which reach a significance level of $\alpha < 0.05$ with $F(1, 10) = 8.00$ ($p = 0.02$).

Last, H_2 was not confirmed (see also Jipp, 2007): The average duration of a task-irrelevant operation in relation to the average duration of an operation did not change overall four practice trials. The probability of its existence does not reach the level of significance of 5%.

Table 1. Results of the general linear model analyses with repeated measurements to test the hypotheses

	Source	Value of the Test Statistic	Probability	Effect Size
H_1	NIO	$F(3, 30) = 5.07$	$p = 0.01$**	$f^2 = 0.34$[1]
H_2	DIO	$F(3, 36) = 2.14$	$p = 0.11$	$f^2 = 0.15$[2]
H_3	DO	$F(3, 30) = 7.15$	$p = 0.00$**	$f^2 = 0.42$[1]
H_4	NST	$F(3, 30) = 4.80$	$p = 0.01$**	$f^2 = 0.32$[1]
H_5	NA	$F(3, 30) = 3.60$	$p = 0.03$*	$f^2 = 0.27$[1]

** highly significant effect with $\alpha < 0.01$; * significant effect with $\alpha < 0.05$
[1] large effect, [2]medium-sized effect.

3.2.4. Conclusions

The hypotheses $H_1 - H_5$ aimed at testing the major assumptions regarding the proposed cognitive processes underlying the continuum between the different modes of human behaviour.

It was hypothesized, that, when confronted with a so far unknown environment, an internal representation of the environment is built. Exploratory behaviour takes place in order to complement the available sensory and auditory information. The inferential statistics applied demonstrate that the proportion of these goal- or task-irrelevant operations declines when the environment gets more familiar (see H_1). In contrast to the relative number of task-irrelevant operations, however, the average duration of the task-irrelevant operations in relation to the average duration of any operation does not change overall practice trials (see H_2). Hence, the difference in duration between a task-irrelevant operation and an average operation demonstrates that the acquisition of the information of interest does not differ. One reason could be that the execution of the exploratory behaviours took longer than the information extraction.

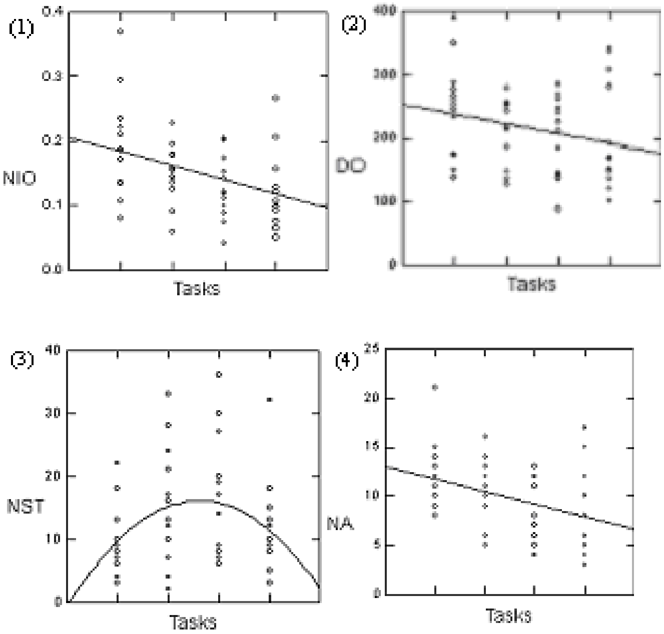

Fig. 2. (1) Scatterplot with a linear smoother demonstrating the course of change of NIO overall four practice trials. (2) Scatterplot with a linear smoother visualizing the change of DO overall four practice trial. (3) Scatterplot with a quadratic smoother showing the change of NST performed overall four practice trials. (4) Scatterplot with a linear smoother demonstrating the change of NA performed overall four practice trials.

It was further discussed that different ways of executing the operations are tested regarding their efficiency. In order to analyse, whether such testing actually takes place, two hypotheses have been formulated. First, the average duration of an operation is expected to decrease (see H_3), as better ways of reaching the goal are found. Second, different combinations of operations are tried out (see H_4). Both hypotheses yielded empirical support. The effects differ, however, in their shape. While the average duration of an operation clearly decreases linearly, the change of the number of strategic changes follows an inverted u-shaped course. Hence, testing different combinations of operations takes place at a later stage in getting familiar with a new environment.

After having built the internal representation of the environment and after having complemented it with feedback about the success of different realizations of the operations, the operations are grouped and no longer perceived as single operations. Instead, actions develop. To test this assumption, the number of actions has been counted which was expected to decrease with the number of practice trials performed (see H_5). This hypothesis was also confirmed.

Summarizing, the empirical results mainly support the theoretically derived assumptions about human behaviour and its underlying cognitive processes when adapting to a new and so far unfamiliar environment.

3.3 Practical Implications

The conducted study and its results have practical implications regarding the realization of intention estimation behaviour:

First, it has been demonstrated that human behaviour changes in the course of adapting to a new environment. Hence, the familiarity of the environment needs to be considered.

Second, the approach to intention estimation on the basis of probabilistic methods, does better work in familiar situations compared to unfamiliar situations. This is the case, as in familiar situations behaviour does not change in order to achieve the same goal. The optimal way for achieving the goal in question has been defined on the basis of mental simulation and practical experiences. Hence, variations in human behaviour do not take place.

Third, in unknown situations deeper reasoning processes and problem solving mechanisms from the actor must be considered. Only, if the intention estimation behaviour can mirror the human way of deciding on the next action, it can provide a valid estimation of his/her next behavioural goal. One potential way is e.g., the decision ladder developed by Rasmussen (1986).

4. CONCLUSIONS

On the basis of problems with existing powered wheelchair control and with existing solution approaches that do not tackle those problems in a comprehensive manner, it was argued that intention estimation should be based on the actor's cognitive processes. Considering especially the theory of direct perception and action (Gibson, 1979), Suchman's (1987) situated actions and activity theory (e.g., Leontyev, 1978), a continuum between different modes of human behaviour was introduced and cognitive processes as underlying this continuum discussed. Major assumptions underlying the continuum and the worked out cognitive processes were tested empirically with wheelchair users and, to a great extent, be confirmed: When confronted with an unknown environment, more exploratory activities are conducted, which complement visual information in order to build an internal representation of the environment. This representation is used to mentally simulate the effect of operations. Feedback from goal-oriented actions is further used in order to define an optimal way of achieving the goal in question. Only after both the internal representation and the way of achieving a goal are specified, operations become automated and are expected not to be subject to change. On this basis, practical implications for realizing a comprehensive intention estimation behaviour have been introduced. Most importantly, it has been discussed that existing probabilistic intention estimation methods are not sufficient. Future realizations should consider the familiarity of the environment; it should make use of knowledge about human problem solving behaviour especially when confronted with an unknown situation and can be based on probabilistic methods in very well-known surroundings.

Future research will demonstrate, whether such an advanced method of intention estimation will actually reduce the troubles especially severely disabled people face with controlling their powered wheelchair. Further, it is aimed at generalizing the conducted research to other technologies, which closely interact with a human being and investigate whether similar results can be achieved.

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