5. Discussion of Case Study Findings

5.1 Effectiveness of the Smart Wheelchair

The case studies indicate the breadth of areas of improvement which can come from improved mobility. They show how these improvements both *extend* into learning, play, communication and socialisation, and *depend* on being nurtured in such functional settings.

As far as the direct use of powered wheelchairs is concerned, our cases spanned children who used the Smart Wheelchair as an effective mobility training aid through to those who will, we believe, always achieve their mobility via augmentative controls, registering successes in both groups.

When introduced and exploited as part of an integrated curriculum, staff also reported significant improvements in children's social skills, and as a result of this, more opportunities for meaningful functional communication. When their circumstances were constructed appropriately, children took advantage of their opportunities to explore, and their inquisitiveness fed back effectively into their persistence in learning the necessary skills. Social and exploratory improvements both in turn open yet more opportunities to extend other curricular areas.

More directly, the video records show clear gains in the patterns of interaction both between child and human partners, and between child and chair control system. We feel confident that skills are being transferred. Moreover, close examination of the video sequences (both coded and uncoded) show changes in the interaction patterns of teachers to children, with less anticipation of passivity in the child on the part of adults.

The studies also reveal improvements in posture and physical skills.

None of the children appeared to suffer as a result of their chair work. The chair is safe in a supervised setting - no accidents took place in the three year programme to either the children, or their environment, or people in it. The newer tools are improving safety features further - soft bump and collision avoidance tools will further help allay fears for other children in crowded settings. We were also concerned that children might become overdependent, and reduce their efforts in other mobility acts. If anything the opposite effect was noticed, with children who had extended access to their chairs appearing to appreciate the value of independence more, and working hard to achieve it in other ways (an example being the young boy who began to try to operate his manual wheelchair after watching Smart Wheelchair work). Fears about poor effects on posture of long term chair work also proved groundless. In a number of cases, posture seemed to *improve*, possibly due to the active effort needed to control the chair: motor skills certainly benefited.

However, although nearly all children proved to be motivated by their experiences in the Smart Wheelchair, the spread of developmental gains was wide over our case studies. From the pilot studies, we had expected there to be individual differences, and were prepared for these to be quite subtle interactions between abilities, personality, and developmental stage. In the event, these individual differences did not seem to be the predominant feature determining progress.

When an able person learns a new skill, we know what to expect of them. Our own experiences tell us how long it takes to learn to spin a top, or ride a bike, or operate a word processor, or drive a car. We know, too, how much variation there is between people's abilities to learn. It appears to us that this understanding and the expectations which it should generate is somehow failing to be applied when planning learning environments for disabled children developing similar skills. Driving a Smart Wheelchair needs something of all of the abilities above: the reader should compare the opportunities for extended learning which some of our case study children have had, with their own skill learning experiences. We now turn to why this should be so.

5.2 Factors affecting Success

5.2.1 Environmental effects

There are many areas of interplay between development of specific mobility-related driving skills, and broader areas of education, which make it difficult to introduce tools like the Smart Wheelchair in isolation from other learning and communication aims and goals. Some aids (like spectacles) need little in the way of training. Others (especially complex augmentative systems) need careful introduction and a lot of practice. A Smart Wheelchair certainly needs practice. However, for that practice to be effective for children who are conditioned to failure, it must produce practical benefits for the child. These benefits need to be seen on a day-to-day basis: no-one will persist in using glasses if they are only available during practice sessions.

To make a system as complex as a Smart Wheelchair available to a child for extended periods means a commitment on the part of staff. This investment must also pay off for them.

In the event, the environmental differences between the case studies turned out to be the dominant factor in determining degree of success. Comparison of the long-term study chart show very large differences between the opportunities offered to children, both in terms of time-on-task, and the degree to which children's learning environments were tailored to take advantage of the Smart Wheelchair. In the best cases, children saw the Smart Wheelchair as a constantly available tool, used both at home, school and for supervised outings. In the worst cases, the Smart Wheelchair was used for occasional ‘sessions’ (in some cases only prompted by the appearance of the evaluator), unconnected with other activities. These differences strongly influenced the outcomes.

Of those children who had least opportunity to use the Smart Wheelchair, the project team felt most disappointed about Cameron (the very young child), and Ross, though for different reasons. In Cameron’s case, it was frustrating to see increasing reports of passive behaviour after his first teacher left, whilst a tool with the potential to reduce such passivity lay little used. It was also difficult to understand, since school staff felt the chair to be one of the biggest motivators for him. In Ross’s case, we clearly did not succeed in convincing the school team that the most value to be got from the Smart Wheelchair in his situation was not so much improved mobility (we could at best have only complemented his other evolving strategies), but in setting up structured exercises aimed at improving planning, symbol use, estimation, and other educational goals.

Any project-based intervention into day-to-day school or therapeutic practice, technological or not, will be at risk if the teaching team is not enthusiastic (or is constantly changing), or if the project is too novel to articulate with the design of the school curriculum. In Scotland, common curriculum guidelines are emerging for children aged 5 to 14 years, and these include children with special need. The clear implication for the Smart Wheelchair (and for other new technologies) is that work must now go into relating technological opportunities to these national aims, therefore enabling school staffs to specify and use them effectively. The Smart Wheelchair team have latterly put a large proportion of their resources into laying the foundations for such work, by producing and testing training materials; creating booklets of suggested activities; and proposing a pilot study into more formal links with the Scottish *5-14* Guidelines.

5.2.2 The need for a curricular base for dissemination of innovations

The Smart Wheelchair is by no means the only technological aid to learning or communication to suffer from patchy take-up because of different perceptions of the relevance to required and ongoing day to day teaching, learning and assessment activities. It is often claimed that identifying and promoting centres of excellence, and highlighting the activities of inventive teachers will lead to widespread adoption of those practices by osmosis. Our evaluation shows, as usual, that while some teachers and therapists are quick and inventive, and while some environments encourage their development, others increasingly see such efforts as standing apart from the demands already placed on them, and do not take up innovative practices. For busy teachers and therapists to see the relevance (or, in some circumstances, to legitimate the allocation of time and resources), there are two prerequisites: a curriculum structure into which the technology fits, and clear indications of how it contributes in ways which would otherwise be difficult, expensive, or impossible.

Fortunately, at the same time as CALL were developing and evaluating the first batch of ten Smart Wheelchairs, major changes in the Education system have been taking place. In England and Wales, these have taken the form of the introduction of the National Curriculum and its close Scottish relative, the Guidelines for the 5 to 14 Curriculum (which has come to be known as *5-14*). Recently, at a conference in Jordanhill College, Glasgow, a group of working parties reported on the adaptation of the *5-14* guidelines for children with special needs (*Support for Learning: 5-14*). It is now widely recognised that the principles and structures offered by *5-14* bring much of potential benefit to special children. The teaching and therapeutic community is also aware that staff will need a lot of support in the years to come as the curriculum proposals move from statements of principle and approach to classroom practice.

This means that we are now in a position to make a contribution to more structured dissemination and use of the techniques pioneered in the Smart Wheelchair projects. The Smart Wheelchair is a maturing piece of technology, already in use in several schools. The *5-14* curriculum and the guidance offered by the working parties offer a framework recognised by teachers, and enthusiastically demanded by parents, into which the Smart Wheelchair's curriculum developments can fit. The SOED Inspectorate helpfully believe that *5-14* is inclusive: **all** children lie within the framework.

We are therefore undertaking a project which will apply our experiences in developing and evaluating the Smart Wheelchair to the production of both general and specific guidelines and exemplars for teachers and therapists wanting to use the Smart Chair in the *5-14* curriculum context. The general booklet will help teachers who have no experience of the Smart Wheelchair to decide if such a tool would be useful to their child. The specific materials exemplify how, at a practical level, curricular goals may be achieved.

This is an enabling project, which itself will lead to and underpin other activities. The most direct will be to use the materials to support the broadening base of Smart Wheelchair users, testing and refining them as necessary. The second aspect we expect to follow up will be the relationship between the *5-14* Smart Wheelchair materials, and those needed to support the National Curriculum in England and Wales.

5.3 Unfulfilled Goals

The evaluation project failed to address the use of the Smart Wheelchair in more advanced educational areas. We had hoped that at least one of the children would have been able to use the chair as part of a curriculum which included LOGO-like micro worlds for learning estimation, planning skills, and perhaps some number work. In the event, the aims for the children were much more focussed on early learning, mobility itself, and communication: the wider application of the Smart Wheelchair remains untested.

We believe that part of the reason for this is that despite the success of exploratory microworlds in mainstream schools, they are relatively novel in special education. It remains one of our goals to at least bring an awareness of the benefits of some of the established LOGO methodology and materials into the decision-making processes which define the curriculum for a Smart Wheelchair -using special child. We hope to do this in our current pilot project on *5-14* Curriculum and the Smart Wheelchair.

There was also little opportunity to try more complex integrated systems involving either commercial communication aids or links to computer-based-learning (with the exception of the young man who was moving from chair control to mixed chair and communication, although even here, the systems were all produced by the project team, and did not include external aids). The mix of children and the aims defined for them precluded such work during the present project. However, we feel strongly that this area will need attention in the future, probably even for some of our current project cases as their needs change.

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6. Products: Material and Training Outcomes and Product Testing

In our project proposal, we said this about the outcomes and products we envisaged

> *"The project worker will be responsible for the generation of both tangible project products, and intangible (but vital) influences during project development.*
>
> ***Dissemination Products***
> *The most important product will be a series of documents which will inform and guide teachers, therapists, and others in how to set up, adapt, and use the chair in a variety of curricular, training, and assessment sessions.*
> *Related to the production of these written materials will be the design and running of a short series of seminars on the use of the chair.*
> *Since we believe that the weakest aspect of much Research and Development work is the dissemination of results in a practical and concrete form to potential users, we rate the production of literature and courses highly in priority. We shall also be seeking effective ways of dissemination through appropriate networks, in the belief that a combination of direct influence (through the project schools); course and seminar attendees; and distribution of practical guides through existing networks, form a more powerful approach to dissemination than through academic papers or journal articles (though these have their place).*
> *One of the tasks of the team is to determine what literature is needed. However, we presently believe that the documents needed include:*
>
> - ***A Brief Introduction to the Smart Wheelchair***
>   *an overview which can serve as introductory course notes, and to inform new enquirers.*
> - ***A Practitioner's Guide to Initial Assessment of Children and Adults***
>   *highlighting how to determine if the chair might be of use, what aims might be practicable, and how to find out what adaptations might be called for.*
> - ***The Roles of the Smart Wheelchair in Teaching and Therapy***
>   *a detailed handbook which relates the chair facilities to the aims and objectives of teachers and therapists involved in planning, intervention, and devising observations and assessments in the areas of interpersonal communication, special educational curricula, and mobility training. This book will be the central product, and will include case descriptions, suggestions and examples, and distilled results of observations made during the wheelchair evaluation period. In particular, it will emphasise the profile of use and adaptation needed during a child's development of skills, and will seek to avoid inappropriate static models of curriculum design by stressing the potential for observing progress and responding to observed changes.*
> - ***Setting up the Smart Wheelchair***
>   *hints, tips, and procedures on*
>   *- seating,*
>   *- switch and other control positioning,*
>   *- choosing tools.*
> - ***The Wheelchair Playbook***
>   *a collection of user-community-generated ideas on wheelchair use: introducing the new child, activities for play and exploration, motivation, communication.*
>
> *The researcher will also be responsible for field trialling the first two of the three other documents below (which will be produced by the technical team), and for reporting on their usability, quality and accuracy:*
>
> - ***The Smart Wheelchair Technical Manuals***
>   - *User Manual*
>   - *Technical Setting Up*
>   - *Maintenance Manual"*

This section discusses how these aims have been met.

6.1 Training and Dissemination: Courses and Associated Materials

Appropriate support documents and courses have both been produced, and the materials are included as Annexes to this report. We have:

- run **introductory courses in the CALL Centre and in schools** for project teachers, therapists and parents, backing these up with appropriate teaching materials (see below).
- run **awareness workshops** for the wider professional community in Scotland.
- mounted a **one day conference on the Smart Wheelchair**, with presentations by both the CALL team and teachers, therapists and parents.
- designed and run (with EEC help) **a five day, in depth course on how to use the Smart Wheelchair**, aimed at multidisciplinary teams: the first course was made up of teachers, speech and physiotherapists, psychologists, an engineer, and administrators.
- presented the Smart Wheelchair Project (both design and formative evaluation) at **national and international conferences**.

A summary of dissemination activities is given in **Annex 9**.

We have noted elsewhere in this report the problems of integration of the Smart Wheelchair into schools' curriculum. One implication of the solution we suggest (that of promoting the relationship of the Smart Wheelchair with the 5-14 Curriculum Guidelines) is that the materials we have produced will inevitably need recasting into that mould.

6.2 Materials for Teachers and Therapists

Undertaking the dissemination work above has allowed us to generate a number of introductory documents, each aimed at different audiences.

- **Introducing the Smart Wheelchair. Annex 7** shows a short form, intended for first-contact introductions.
- **Smart Wheelchair Training Pack. Annex 8** shows the materials for a full training course. This latter document (together with supporting papers and notes) serves both as general course material, and the basis for dissemination of information on specific topics.
- **Using Smart Wheelchairs.** To support these courses, and as outreach to those people not able to attend formal training or seminars, we are now preparing an informal book on the Smart Wheelchair (in press).

The team have completed these associated documents, which have been in use throughout the project:

- **Guides for Mobility Training and Assessment (Annex 5)**
- **Wheelchair Playbook (Annex 6)**

User Handbooks (Annex 4) and **Technical Documentation** have also been created and field tested.

We now realise that the issues raised by the use of the Smart Wheelchair, and the range of potential professional and parental readers, are too diverse to be served by a small number of all-embracing documents. We have therefore moved from writing monolithic descriptions to designing sets of smaller, reusable materials which can be drawn together to meet different needs. As a result, the training course shown in Annex 8 has been written in modular form. Together with the 'Guides for mobility training and assessment', sections of these training materials also satisfy some of our aims for what we had thought of as the 'Practitioners Guide to Initial Assessment'. Similarly, materials needed for disseminating information about the 'Roles of the Smart Wheelchair in Teaching and Therapy' are also contained in Annex 8, together with aspects of the 'Wheelchair Playbook'.

We are convinced that such modular material can also be delivered in interactive forms, and we are currently exploring how our paper-based resources can be embedded into multimedia hypertext formats, enhanced by video fragments from our extensive recordings of children in the programme.

6.3 System Effectiveness and Design Changes

A major part of the evaluation team's work was concerned with providing feedback from schools to the design team on the effectiveness of the Smart Wheelchair. In our proposal, we said of the formative role of the evaluator:

> *"As well as their role as co-devisor and tester of innovative programmes and assessments and producers of the written products [...], the researcher will be contributing in other ways:*
> - *as **progress chaser**, s/he will be the main link between design team and schools.*
> - *as **trainer**, s/he will be responsible both for keeping the school team up to date on results, and for designing the outreach exercise.*
> - *as **support for school**, s/he will reduce the disruptive effects on the schools of new, and probably unreliable, technologies and practices."*

The evaluator fulfilled these roles in each of the three schools, on a time-sharing basis. Balancing the roles of information-gatherer and detached analyst with those of assessment team member, supporter, trainer, and go-between is not easy: there are inevitable compromises. Helped by her feedback, many important design changes and refinements have been made to the Smart Wheelchair. These include changes to:

Bumpers

The collision sensors have two functions: to detect all collisions quickly, and to absorb the force of a collision when it occurs. There are bumpers situated at the front and rear of the chair, each consisting of three sensors mounted in foam (as opposed to 1 sensor in each bumper in the prototype: the use of several sensors for each bumper allows the software to make decisions about the angle of the collision). The bumpers are mounted on steel brackets bolted to the wheelchair chassis. The early chairs used pneumatic sensors for detecting collisions. These worked reasonably well and provided a good compromise between detecting collisions and absorbing the force of the collision. However, they were bulky, expensive to manufacture, and the evaluator reported reliability problems due to air leaks.

A second design was produced and fitted to 9 of the chairs. This again consisted of foam bumpers with sensors embedded into them but this time the sensors were strips of pressure sensitive material whose resistance decreased with pressure. This reduced the cost and simplified the design by:

- replacing expensive pressure switches with cheap electronics.
- replacing air tubes with single-strand wire.
- simplifing the foam covering of the sensors.

In addition the foam bumpers were fixed to the steel brackets with velcro, allowing the bumpers to detach from the frame if they became caught. This reduced the risk of tearing: the teacher could then simply fix the bumpers back in place.

While 'Bump and Turn' proved useful for giving single switch users the opportunity of crunching round their environment to explore it, as a functional mobility system it leaves a lot to be desired. A more useful 'Bump and Turn' tool would make use of the pilot's perceptions and skills by giving control over the distance reversed and the direction and angle of turn. This in turn would require the user to understand that the switch which previously moved the chair forward has now taken on several different functions throughout the bump and turn manoeuvre. Immediately after the collision the switch will move the chair away from the obstacle until released; then it is used to select either left or right as prompted by the Observer; then it turns the chair left or right until released; and finally moves the chair forward again. This sort of switch use has parallels with single switch row-column scanning in terms of the changes in switch function and subsequent cognitive demands upon the user, but is considerably more demanding than the original 'automatic' bump and turn. Such a 'user-controlled' set of bump tools has yet to be tested in the schools.

The bumper design is still evolving, in part to make the system more robust, and in part to incorporate the ultrasonic sensors which form the basis of the collision avoidance system.

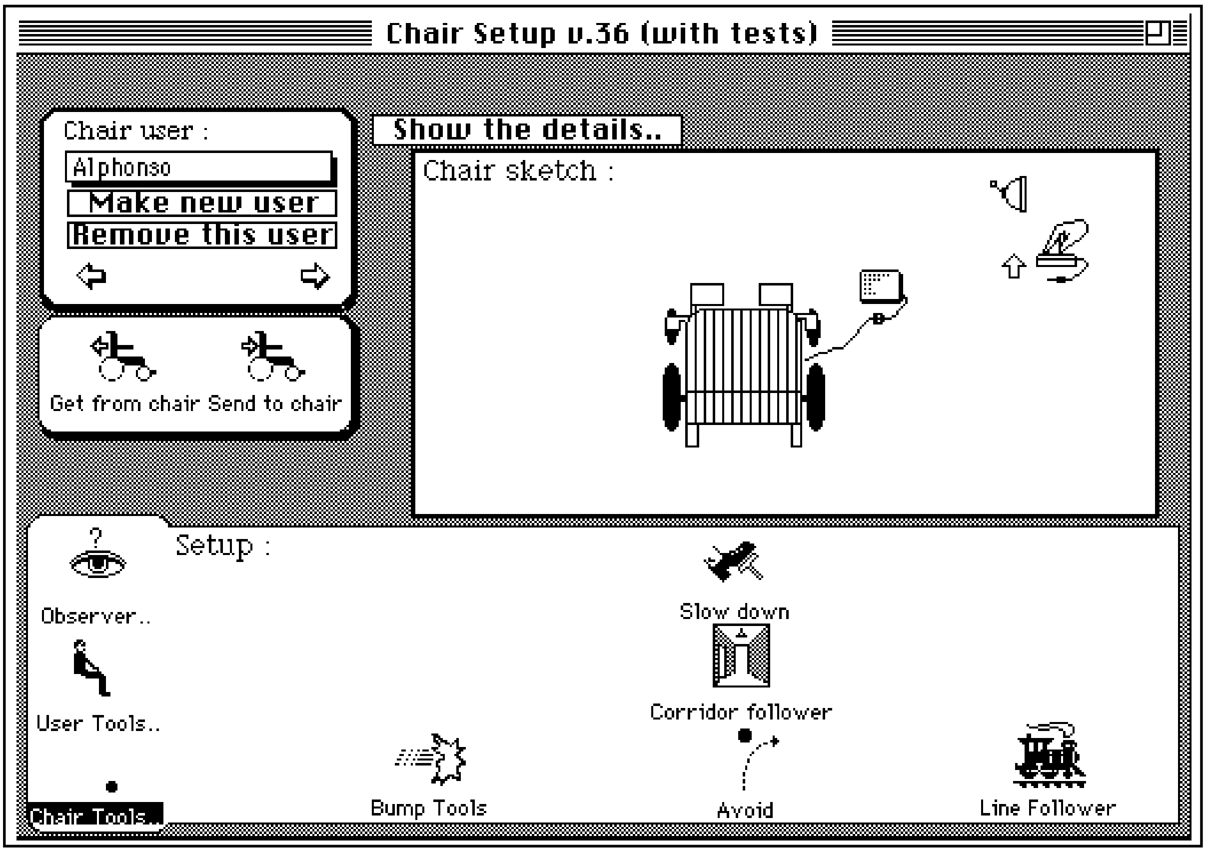
Enclosures

A major design issue during the project revolved around how many units were needed to house the electronics, the tradeoff being between modular costs; communication and wiring costs; user convenience and ease of understanding the system; and ease of access. For example, during the project the speech synthesiser has migrated from being a standalone item to being incorporated in another unit, reducing the wiring 'rats nest' considerably.

User Setup Tools

The Smart Wheelchair is highly tailorable: it follows that much effort went into devising user setup tools which are easy to understand and handle. At present, there are four ways of tailoring the chair to different user's needs. The least useful, from a teacher's or therapist's perspective, is via the polyForth system. More accessible (but more limited in scope) is the hardware ToolBox.

An alternative technique is to pass control codes to the chair via the RS-232 serial line. However, these are somewhat arcane and give little support to the teacher in visualising the current configuration, or in storing and recalling complete setups found particularly useful. (This latter requirement is most important when a chair has multiple users, and reconfiguration take place often). To meet these needs, the evaluation team developed the Macintosh based package shown below: with it, teachers can see at a glance the current configuration, can store sets of different configurations, and can exchange the setups by pointing at icons rather than through text interactions.



Computer-based setup tool

Switches and Controls

Control design or specification was probably the most intensive area of evaluation feedback. Wherever possible, existing controls already used by a child (for accessing computers, communication aid or activating toys) were utilised to drive the chair. However, in some cases special switches, adapted joysticks or computer-based communication and control systems had to be designed and built. These included -

Finger Switch

This switch was designed to allow someone who has good control over flexion and extension of a finger to operate the chair. The switch is based on a hall-effect sensor which detects the presence of a field produced by a small magnet. Both magnet and sensor are mounted on a cotton glove. The switch has the advantage of not being a targeting device: the user does not have to look at it during operation. Where a rider's proprioceptive abilities are poor or not well developed; or where multiple demands are being made on visual attention (as in the case of driving whilst operating a scanner); or where fine motor control is possible in one part of a limb which is otherwise poorly controlled, such switches can be very helpful. Accidental activations are reduced, and attention can be focussed elsewhere. Both of these points are desirable in a dynamic environment such as a powered wheelchair.

Analogue Joystick Interface

For one child, the ability to plug a normal wheelchair joystick into the chair was considered desirable, giving the user proportional control. An interface was designed which allowed the joysticks removed from the DCL motor controllers to be plugged into the joystick socket on the SwitchBox. When the joystick is plugged in, the chair automatically recognises that a proportional control is present and configures the software appropriately (and motion tools are disabled).

Wheelchair Scanner

A scanning system was designed that combined both communication and chair control. A number of commercial systems were investigated but none offered all the facilities required. These were:

- the ability to animate the choice prompt displays.
- the availability of voice prompts and voice confirmations (using different voices for each).
- Serial communication with the wheelchair.
- the ability to accept ascii control strings *from* the wheelchair.
- the ability to incorporate digitised pictures as prompts.

The system was therefore programmed in HyperCard for use with a Macintosh PowerBook computer.

For more details of the overall design evolution, see the DRC Technical Report on the Smart Wheelchair.

As a result of the continuous feedback, the Smart Wheelchair is now a stable and robust design. Failures are rare, and usually confined to lifed items such as bumper foam. Using the experiences gained through the twelve school-based chairs, a redesign of the system has taken place (funded by the associated EEC HORIZON project). The redesign enhances the second-stage Smart Wheelchair for use with an adult population, taking into account new technologies and standardisation developments within the rehabilitation industry. The same chassis is currently in use, but many other details have changed.

Future development should concentrate on enhanced tools to help children in their transition to more complex environments beyond school. Part of this will involve improved integration of the Smart Wheelchair with other aids. Specific attention is still needed to enhance collision sensor life.

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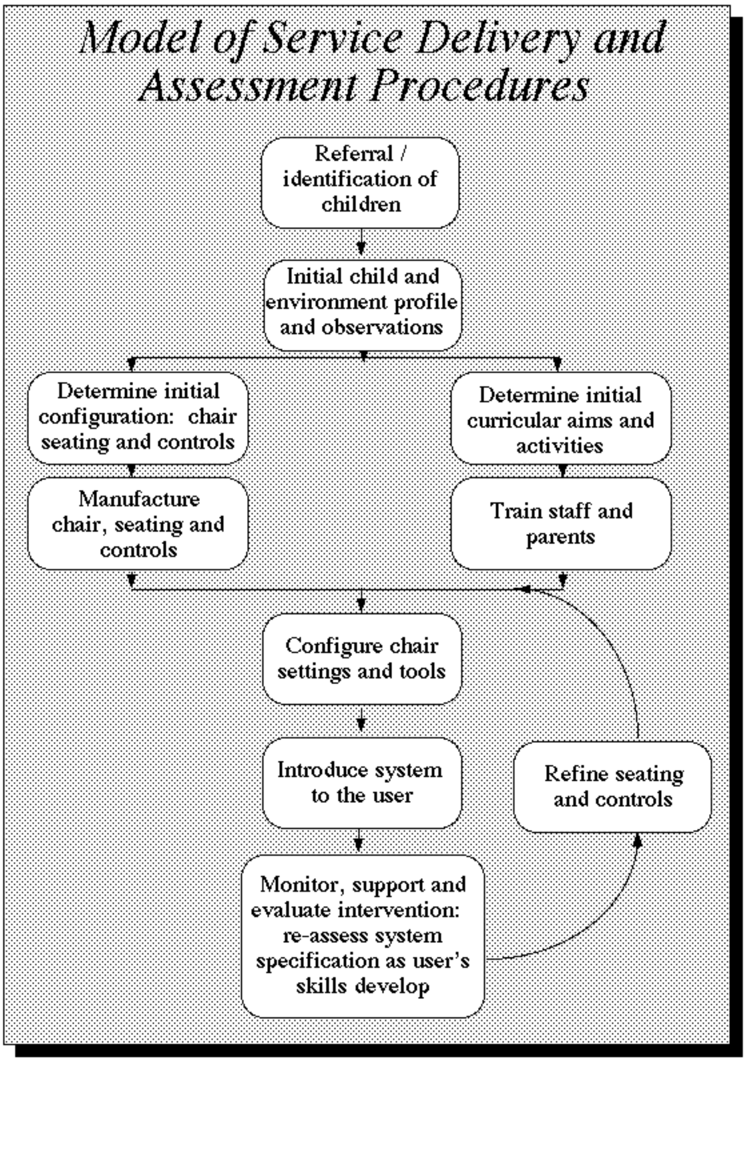
7. Future Planning: Manufacture and Service Costs, and Potential Users

7.1 System and Support Costs, and Provision of Service and Support

In this section, we outline the costs of acquisition and modification of the Smart Wheelchair, giving indications of associated support costs. These figures are derived from the case study wheelchairs, and should be treated with caution. Extrapolation of costs from prototypes and projects to products and services is difficult. The main reasons are uncertainty about how services might be provided, and the best manufacturing route. Because we cannot be accurate about future provision environments, we have adopted the following strategies.

- Firstly, we estimate service costs in terms of professional time, not money.
- Secondly, we note (but do not attempt to quantify) where component costs are changing.
- Finally, we make no attempt to surcharge any of these estimates with the necessary costs of staff training, travel, personal or corporate insurance, standards testing and clearance, or product research and development which will be part of any larger scale commercial or quasi-commercial ventures.

We take service aspects first.



CALL's action research project put in place a simulated service environment in order to refine our understanding of what is involved in delivering and supporting continually extended systems. This environment (consisting of manufacture of basic Smart Wheelchairs, assessment, provision of training, seating and control adaptation services, telephone advice, and maintenance) is integrated into the cyclic model shown on the previous page. The stages involved are:

Initial referral

As with communication aids 'referral' is not merely an administrative preamble to the child being seen by the team. Rather, it is a filtering process: a mixture of discussion about the state of the child and his/her environment, the aims for that child, and the appropriacy of the Smart Wheelchair as a tool to help meet those aims. We have found that time is well spent here, and therefore the referral process often involves preliminary discussions between teachers, parents, and therapists, and both technical and augmentative techniques staff. It is not uncommon for this process to take two or more working days, aggregated across the professional staff of both school and centre.

Assessment: Child profiling and observation

This exercise fleshes out the details provided in the initial contact report and discussions. It will involve a meeting between teaching and therapy staff and the wheelchair key person (up to half a working day), together with initial observation and video sessions, preferably in both home and school (taking the wheelchair team member a further working day). Follow up planning with technical staff takes the form of discussions with technical staff, and the writing of a preliminary profile and strategy. These may take a further working day.

Assessment: Configuration design for seating, controls, tools

With the initial profile to hand, technical staff undertake detailed measurements for seating and controls prior to deciding whether off-the-shelf solutions are possible, or if a system has to be built or extensively modified. Usually two technical staff are involved, and the exercise may take a quarter of a working day each.

Assessment: Curriculum / intervention planning

Once the system is designed, the wheelchair key member then discusses and refines the intervention plan with school staff. This discussion may take one or two hours. Any changes need then to be incorporated into the planning documents.

Manufacture and adaptation of chair, seating, controls

Basic system costs are discussed later. The costs of adaptation can vary greatly. It is rare that seating and control systems can be created with less than a person-week of effort: usually more.

Initial staff/parent training

Initial training sessions will involve at least one school staff member (maybe more if the school is new to the Smart Wheelchair, or if the tailored system is particularly novel, or if a team teaching approach is being adopted), together with parents and one member of the wheelchair team. (In our project sessions, there were more team members, because of the experimental nature of some of the designs. In production, all training could be carried out by one wheelchair team member.) These sessions take around two hours.

Initial chair configuration

Software changes were often needed in the project prototypes: however, such forms of configuration are becoming rarer as the facilities of the Toolbox and its more sophisticated computer-based counterpart expand. The configuration exercise is now taken as part of introduction and training.

Introduction and initial training

For an experienced school team, it is unnecessary to have a wheelchair team member present during initial training. If the school team is not confident, however, then up to three or four introductory sessions might be set up, each with perhaps an hour of contact by teacher and team member.

Monitor and re-evaluate

Refine and reconfigure seating, controls, intervention plans, and tools.

The degree to which a school might want to call on the wheelchair team to help in re-assessment and re-configuration will depend on the school team's experience, the extent of adaptation of seating or controls needed, and the local resources it can call on. As can be seen from the case studies, sometimes the Smart Chair had to be altered considerably over a short period. However, skill plateaux can be quite extended, and the refinements well within the technical competence of the school staff.

Not shown in the service model or the description of resources needed for it are telephone support and maintenance. The reliability of the Smart Wheelchair is currently quite good, but it would be wrong to estimate the mean time between failure (and therefore the maintenance costs) for any commercial derivative.

The validity of these estimates depends in part on the degree to which actual service provision can be set up to match this model. There are several possible service providers. Until recently, the most obvious places to develop expertise in Smart Wheelchair services would have been Health Authority mobility centres. However, rapid changes in health services means that the role of such centres is now not so clear-cut. The Health Service 'market' favours well established services and systems, but makes specialised services which focus on bespoke system designs hard to establish. Our experience suggests that, in the current climate, health authorities are not going to take up novel problems when they cannot solve their present ones. Fragmentation of policy for provision in the name of market forces means that any innovation seeking to find a widely influential launch point is thus likely to be frustrated.

Independent commercial provision is much in favour as a health and education service solution. The problems here are that there needs to be a coherent market for the hardware systems to be in place before commercial service support can build on it. One technique used by some Communication Aid manufacturers is to bundle initial assessment and training costs with systems. However, a major difference between service and support needed for Smart Wheelchairs and that needed for augmentative communication aids is the degree of adaptation, and the regularity of review and changes. Service bundling has also come under increasing pressure recently from criticism about independence during assessment. Such service provision also needs up front investment by manufacturers, who are wary about individualised products (see below). Finally, the problems of geographical distance are severe, especially when it comes to seating and control adaptation.

A third approach we have considered is more inhomogeneous in nature, but is probably more appropriate in the current climate. It involves identifying, in particular regions, potential collaborative groups of cross-disciplinary specialist centres, and then enlarging their collective role to the provision of smart wheelchair services. The most obvious centres are those already involved in provision of wheelchairs and seating: however, they are not the only candidates to be a regional focus. Given the close relationship between the Smart Wheelchair and other augmentative systems, it makes sense to use augmentative communication centres where possible. Some of the best of these are funded by local education authorities, or are national centres with special local responsibilities.

While it is not clear that government would support centralised services, they may see the advantages in efficiency to be gained by building on existing skills in this way. (In any case, centralised services suffer from well known disadvantages of geographical remoteness and lack of patronage by local authorities and health boards under pressure to find local solutions. The Centre-Satellite model promoted by CALL in the early eighties has taken a decade to come into effect, which is too long a timescale: the innovation would atrophy and die in the meanwhile.) We suggest that a workable strategy would be to identify interested existing service providers, enable them in their new role by supplying them with basic assessment tools and training, and further supporting them through central loan services (much as is currently done for communication aids).

This last strategy also helps alleviate problems typical when new technologies developed by small independent groups are brought to market, namely the severe skills shortages due to lack of apprentices. Working through established centres would enable the service providers to ramp up in a controllable manner, without their other commitments (to manufacturing, standards testing, and development) suffering. However, such a strategy would take time to put into place, and would need constant attention and repair: the price to be paid for lack of national policy is local administrative waste.

We now turn to hardware costs and manufacturing issues, beginning with an outline of the costs associated with tailoring and adaptation of the project chairs. Note that in the following two tables, component costs tended to be small in comparison to labour costs, and most items are therefore estimated on the basis of construction time.

Seating

Our partners in Princess Margaret Rose Hospital Bioengineering Centre assessed and provided seating for each chair user. In some cases complete seats were designed and manufactured from scratch, while in others a frame was built to accept a modified Britax car seat or the child's seat insert from their manual wheelchair. A summary table of seating systems together with an estimation of costs (inclusive of parts and labour) is shown below.

USER	SEATING SYSTEM	EST. COST
Individual	individually designed and manufactured (foam, wood and metal)	£ 1,000.00
Individual	Modified Britax car seat with sub-frame	£ 500.00
Individual	Modified Britax car seat with sub-frame	£ 500.00
Individual	Own manual wheelchair insert, with sub-frame	£ 300.00
* Mobility group	1 small and 1 medium standard Newton seats	£ 300.00
Individual	individually designed and manufactured (foam, wood and metal)	£ 1,000.00
Individual	Own manual wheelchair insert, with sub-frame	£ 300.00
Individual	Own manual wheelchair insert, with sub-frame	£ 300.00
Individual	individually designed and manufactured (foam, wood and metal)	£ 1,000.00
Individual	Modified Britax car seat with sub-frame	£ 500.00
Individual	individually designed and manufactured (foam, wood and metal)	£ 1,000.00
Average		**£ 610.00**

* The mobility group are the three children using a shared Smart Chair to develop driving skills for ordinary powered chairs.

Controls and switching

Some children already had satisfactory switches or controls for accessing computers or augmentative communication systems and so these were adopted as initial switch systems for driving the Smart Chair. Others were assessed by a joint team comprising occupational, speech, and physiotherapist, teacher, parents and the research team and commercially available switches and controls purchased.

However, most of the children were supplied with specially designed control systems by CALL or the Bioengineering Centre. As we described in the case studies, these ranged from a sensor to detect flexion and tension of a fore-finger, regardless of the position of the child's hand in space, to mechanical and electronic modification of a standard wheelchair joystick to provide gated digital output. The table below shows the control systems supplied to each user, with an estimation of the time and component costs required for assessment, design and construction.

These costs are not one-off. Improvement of fine motor and control skills is an aim for almost all the children and so, as skills develop, additional or alternative controls are provided.

USER	INITIAL CONTROLS	ADDITIONAL CONTROLS	EST. COST
Individual	custom finger flexion switch	Custom laptop-based scanner	£ 2,000.00
Individual	modified analogue joystick (Fwd)	lever switch (right steer)	£ 480.00
Individual	custom flush tray switch		£ 450.00
Individual	modified analogue joystick (Fwd)	2 lever switches (left and right steer)	£ 450.00
Mobility group	own/commercial controls		£ 100.00
Individual	lever switch		£ 30.00
Individual	custom squeeze switch		£ 480.00
Individual	custom arm-raise switch	lever switch replaced arm-raise switch	£ 480.00
Individual	modified analogue joystick (Fwd)		£ 480.00
Individual	modified analogue joystick (Fwd)		£ 480.00
Individual	custom switched joystick (Fwd)		£ 390.00
Average			**£ 530.00**

In 1992, the basic chair costs, excluding resources needed in schools to make effective use of the system, looked like this:

Smart Wheelchair supply costings (estimated)

Basic chair (Newton Badger Epic chassis, Control Dynamics motor controller, Smart electronics, sensors, speech sythesiser and labour)	**2825**
Initial assessment (at least 2 person days)	480
Seating:	609
Switches/controls:	348
Chair adaptation (0.5 person days):	320
Staff training (at least 2 person days)	480
Support & maintenance (assume 2 person days)	480
Total support costs	**2717**
Total cost	**5542**

Since then there have been inevitable changes in component costs. Some switches and other controls which we might otherwise have had to hand craft have come onto the market, reducing their cost. The effort needed to build the chair has reduced as a result of engineering redesign, and future highly tailorable communication aid systems such as that being developed by the Comspec project (Lundalv, 1993) will mean cheaper tailoring of more complex integrated communication and mobility systems. Economies of scale are not reflected in the current costings.

On the other hand, basic chassis costs have risen somewhat. The cost of buying a Smart Wheelchair depends on the balance between changes in price and availability of off the shelf or user tailorable systems, and those which need special manufacture, and the degree to which services are bundled with purchase price.

One complicating factor in costing the system is the degree of modularity. It may not be possible to determine what components are needed until assessment has taken place with a trial version of the chair. Changes in specification are also likely later in the cycle of service and provision, and as part of this, some people might want to *downgrade* their system. The project team see three mechanisms to help here. The first is commercial leasing of subsystems for assessment or during the training period for transitional chairs. A second is a loan bank. The last possibility is sale and buy back.

Which of these is workable depends on the eventual service and manufacturing organisation. The CALL Centre has experience of running an extensive loan bank, and see this as a highly efficient aid to assessment services. However, either of the other two would work, albeit at more cost to taxpayers.

Options for manufacture and supply

The following options are open to the team for manufacture of the Smart Wheelchair.

- A commercial manufacturer of wheelchairs or wheelchair controllers could be licensed to manufacture and market the Smart Wheelchair modules as part of their range. The project team have begun discussions with a number of potential commercial firms. However, we are not encouraged by what they say. In a time of recession, manufacturers are resistant to taking new risks which come from outwith their own planning exercises. Moreover, although the market for Smart Wheelchair components is probably not small taken overall, it is highly differentiated, and therefore unattractive to manufacturers who have no real experience in supplying highly tailorable systems.
- A cottage industry could be set up by the development team, following the well established tradition of many other augmentative communication aid teams. We need to be guided here by the large numbers of these enterprises which have failed during the late eighties and early nineties, due partly to the lack of marketing base and the inability to service customers far afield, and partly to the inability to generate enough revenue to support the ramp up process. Put at risk, meanwhile, are the existing responsibilities and career structures of team members, and the further development of the chair.
- A third option is for the team to subcontract production on a small scale initially, and focus their energies on service aspects (which will be controllable if only because supply will be constrained). This strategy will allow the team to establish market credibility, and could work well if combined with the approach outlined above of working to develop targeted regional centres of expertise. This last approach is the team's preferred solution for the interim period. Note, however, that neither economies of scale nor wide availability of the Smart Wheelchair can be delivered by this means.

In summary: service costs for highly tailorable systems outweigh acquisition costs. Although this is accepted by users of other complex systems (such as commercial users of personal computers, who expect to pay ten times the hardware costs of a PC for service and upgrades over its lifetime) it is alien to educational support mechanisms, and difficult in the present climate of any central / local government funding constraints. We therefore believe that Smart Wheelchair provision can only ramp up slowly, and this can best be achieved through extensions to existing regional provision (making good use of non-mobility resources with relevant expertise), backed up by training, assessment packs, and a loan bank.

The manufacturing and service model which can be set up also depends on take up of Smart Wheelchairs. We turn to the potential market next.

7.2 How General is the Need for Augmented Mobility?

Potential users of Smart Wheelchairs

While it was not the intention of this evaluation to carry out a survey of potential users of the Smart Wheelchair, it is clear that some estimation of the degree of uptake is vital for planning chair manufacture and services. There are now clear indicators that the range and number of users could be extensive:

The current wheelchair has proved an effective aid for children who have mobility problems which have proved intractable using conventional powered wheelchairs. Several such children were identified just in the three special schools in the project, and there is every reason to believe that these children by no means exhaust the possible users, even in our sample. Given that the mix of children in our project schools is representative of special schools across the country, it seem reasonable to suppose that at least three or four Smart Wheelchairs could be used in many other special schools for individual users.

Smart Wheelchairs have also proved their worth as transitional training tools, on a shared basis. Some of our case studies had been rejected for conventional powered wheelchairs before using the Smart Wheelchair. We are convinced that a pool of similar border-line, but rejected children exists, and that they could be identified and retrained using Smart Wheelchair techniques. The implication for production is that there is also a market for institutionally owned chairs.

The Smart Wheelchair team is just now beginning to work with adult users of the Smart Wheelchair. That exercise has identified new opportunities for using the relatively unexplored potential of the Smart Wheelchair to integrate with other technological systems (such as workstations, smart environmental controls, and new communication systems) to open up education, training and work opportunities both for adults with stable disabilities, and for those suffering from degenerative complaints. The adult market, perhaps boosted by elderly users, will increase the overall demand for chairs and services to the benefit of younger users.

We have not explored the use of augmentative mobility with some significant groups of disabled or handicapped children, who nonetheless appear as though they could benefit. Among these are children with complex combinations of physical and visual difficulties, for whom exploration is doubly problematic; and children with severe and profound learning difficulties (for whom the original Hull Unibuggy was designed - not to improve mobility, but to shape understanding of cause and effect). We have also not explored the Turtle - like qualities of the Smart Wheelchair in more advanced educational curricular activities. Blind, multiply handicapped children, like many of those in our current study, would be candidates for personal Smart Wheelchairs. In contrast, the other two areas could be served by institutionally owned systems used as part of specific educational programmes.

Most mobility surveys are based on traditional understanding of what powered mobility systems can do and how they are used. As a consequence, they fail to expose much larger potential markets. We should like to see a fuller survey of the market, including the groups above.

The project team have been carrying out some ad-hoc market testing exercises, based on the dissemination activities. They have encouraged professionals who have attended training sessions (and who are therefore in a reasonable position to judge the usefulness of the chair for their own clients) to register provisional referrals (called ‘statements of interest’) in anticipation of assessment services and wheelchairs coming on stream. As an indication of the potential number of users, after one of the one day seminars (held for Scottish teachers and therapists, and presented by a mix of the CALL team, the Schools teams, and parents), the Centre received just under fifty statements of interest. Some features of the responses are summarised below.

Statements of Interest by Region	
Grampian	26
Lothian	7
Dumfries & Galloway	7
Fife	5
Central	4
Total	**49**

(Grampian region provided more than 50% of the seminar attendees.)

The responses were disproportionately biased: heavier returns came from people who knew the CALL Centre and its work well, or who were themselves involved in augmentative techniques.

All three schools currently using Smart Chairs identified children who might benefit **in addition** to those children currently using Smart Chairs: 4 children from Westerlea; 2 from Graysmill; and 1 from Oaklands.

Statements of Interest by Discipline	
Physiotherapists	26
Teachers	20
Occupational Therapists	2
Speech and Language therapists	1
Total	**49**

The spread of professionals returning questionnaires reflects the current responsibility for mobility although it is encouraging that the second largest group is teaching staff. It is perhaps surprising that Speech Therapist referrals are so few given that the majority of Smart Wheelchairs in the CALL project have been used by either classroom auxiliaries or speech therapists, and given that over half the clients were described as having a speech and language problem (see 'Main client disabilities').

Age of Clients	
Under 5	7
5 - 19	34
19+	8
Total	**49**

The seminar placed emphasis on mobility as an education activity.

Main client disabilities	
Severe Physical disability	45
Speech/language problem	25
Visual impairment	4
Learning difficulties	3
Specific learning difficulty	4
Total	**81**

Most children have more than one problem and the medical condition is most often some degree of cerebral palsy.

Intended use for Smart Chair	
Motivation	43
General education/classroom use	37
Speech, language & communication therapy	29
Physiotherapy	29
Mobility	27
Training for powered mobility	18
Occupational therapy	17

The balance of proposed uses for the Smart Chairs indicates the problems which face staff in schools when trying to create motivating activities for children. One slight surprise was the relatively small percentage who saw the chair as a means of mobility training.

Intended location for Smart Chair	
Home	41
School	39
Day Centre	8
Hospital/residential home	8

This particular seminar focussed on children of either school or pre-school age and the statements of interest were skewed in this direction: thus the intended location of use was mainly home and school. We would expect a different result if we presented seminars on the current work for adults.

Smart Chair features expected	
Bumpers/bump detectors	45
Individualised switches	40
Individualised seating	39
Rangefinders	35
Switch interface	25
Motion tools	24
Integrated mobility/communication/computer acces	17
Scanning interface	13
Adapted joystick	13
Line following	8
Other (full assessment)	1

The information on likely Smart Wheelchair features required should be viewed with caution since it is unlikely that staff returning the questionnaires can make precise forecasts on the basis of one day's Seminar. It is evident that there are some areas of misunderstanding: for example, 40 out of the 49 require individualised switches but only 25 seem to want the switch interface needed to connect the switches to the wheelchair. (With hindsight our meaning was unclear in the questionnaire: we wished to separate out those children who already had switches and therefore just required switch access using an interface, from those who require switch assessment and customised switches as well). Otherwise likely features are much as might be expected: most children require switch access, seating, and sensors to avoid damaging themselves or their environment.

7.3 Effectiveness and appropriateness of formative evaluation in the development of new technological systems

We designed our evaluation around formative intervention, planning that the evaluation team would be involved in production and testing of materials, and in day to day support of the teachers and therapists in the collaborating schools. Our proposal made this clear:

> *"As with many other powerful new technological tools, the very breadth of opportunity is itself a development problem. It is not sufficient to offer such technical tools to teachers and therapists merely with vague encouragements to be inventive with them. The last decade's experience with framework (or 'content-free') programs shows the need for well-developed exemplars which can at worst allow teachers not able to do developments of their own nonetheless to emulate good practices of others, and at best act as a spring board for new developments which can feed back into the broader community of users. In our case, the opportunities outlined above form a framework for a series of curricular and training experiments which must, to be useful, lead to the development not only of an understanding of the practicalities of using the chair in classroom and other settings, but should form the basis of tangible dissemination products."*

We therefore favoured the evaluators working in collaboration with the rest of the team.
Was this approach successful?

Formative evaluation can certainly be efficient. This is in part because the evaluator can have several roles (not possible with non-participant observers), and in part because her closeness to day-to-day problems and her adoption of joint responsibility with school staff for some of the outcomes makes communication easier. Given that there was just one researcher with managerial support, it would have been very difficult to have got through the extensive programme of initial choice of children, assessment, profiling, training, adaptation and chair introduction, curriculum support, extended observation and recording, and analysis for the numbers of children and schools involved, without the flexibility which the formative model offers.

We are also content with the product outcomes.

On the other hand, such flexibility brings its own problems. Of these, the most difficult to deal with are undue dependence; timetabling problems; and biased observation.

Undue dependence is a persistent issue. The boundary of responsibility for interventions can become blurred if it is either not properly negotiated in the first place, or becomes unclear as trained participants migrate from the programme.

Timetabling is beyond the control of the research team. Even where schools are committed to the project, their statutory responsibilities come before the needs of external researchers, and delays and slippages are inevitable and unpredictable.

Biased observation can be offset to some extent by techniques such as triangulation, the use of low-inference observation tools, and openness to comment and criticism. However, no-one would claim that the results from this kind of study should be treated in the same way as controlled clinical trials.

As to other aspects: we were disappointed not to have been able to get further with the development of curricular development; and we would have liked more time to deal with the volume of data, particularly from the post-study collection. Both suffered because of our underestimation of how long the process of assessment, initial provision, and training would take, and of the effects of staff changes in the schools. Fortunately, the curricular issues can be pursued under the Nuffield funded 5 to 14 Curriculum Project, now underway.

In summary: we commend formative action research to others introducing new technology: our best advice is to point out its efficiencies to funding agencies doubtful of its scientific rigour. One side-effect should be also pointed out: as a result of this project, three schools have expertise in the use of augmentative mobility, and have incorporated it into their ways of working: and several children are now mobile and socially active who were not before.

8. Conclusions

The Smart Wheelchair has proved itself a powerful tool in motivating and enabling children with poor mobility who might not otherwise manage a conventional powered chair. For such children, it is at its most effective when used as part of an integrated curriculum, itself tailored to the needs of the child. As with other new technologies, putting such a curriculum in place is difficult.

The factors which will allow Smart Wheelchairs to be used effectively in the future are:

- Chair availability
- Service support (including training)
- Curricular support

The project team came to the following specific conclusions:

Safety
The Smart Wheelchair is a safe learning environment for physically, cognitively and perceptually impaired children. Those in our study were generally unafraid of the system, even in the early stages. The most nervous child was the youngest, and he overcame his fear after careful introductory sessions. The Smart Wheelchair is also safe to use, and its self-monitoring systems work well. New tools will improve safety further. We have recorded no regression in children's condition which could be attributed to chair work, or noted over-dependency on the chair. On the contrary, it encourages improvements in the areas outlined below.

Motivation
Smart Wheelchairs and the mobility they promote, can be effective motivators in situations where other stimuli have failed. Children on the project put great effort into operating the chair controls, sometimes over extended periods. Improvements have been recorded in children of all ages, with various conditions affecting their mobility. Even children who have had the disappointment of not being able to control conventional powered wheelchairs have persisted in this new environment.

Developmental improvements
This motivation can be exploited to develop mobility itself, assertiveness, exploratory behaviour, and persistence. Initiation improves in both interpersonal, and person-to-chair interactions. Secondary benefits of these improvements include the opening up of better functional environments for communication and learning. The real-world benefits of improved mobility are encouraging better social interaction and, with it, better communication. Children have also shown improvements in physical tone and control.

Transferability of skills
The skills needed to operate a Smart Wheelchair have proved to be transferable to other situations. Specific skills associated with control, attention, and scanning in the Smart Wheelchair are close enough analogues to those in other augmentative systems for them to be useful bases for development. To make best use of these opportunities, staff need to be aware of potential targets for transfer, and be ready to set up curricular and communication opportunities in which these will be needed. This argues for careful integration of augmented mobility experiences into the day to day activities of the child.

Training for conventional powered chairs
Smart Wheelchairs can also be used as effective transitional training aids en-route to conventional powered wheelchairs, for those children for whom the initial step to analogue control is too great, or where there is doubt about other driving-related abilities such as concentration, vision, or the ability to estimate and plan. It is not always easy to determine if a child will succeed in this task: where learning is slow, the child should be treated in the interim as a potential long-term user of a Smart Chair, with all that implies for long term use. We have doubts about the effectiveness of short-period training sessions without the ability to practice at leisure and in functional settings.

Most effective environments

Complex system technologies like the Smart Wheelchair show most benefit when they are used as integral parts of a broad curricular design. Occasional use is as unrewarding in the curriculum as it is for general mobility. Sharing chairs leads to counterproductive timetabling problems, and lack of perceived worth by the rider of a non-owned resource.

Time-on-task

More variability in the responses of the children on the program can be attributed to lack of opportunity to practice due to non-integration with other activities than to individual differences in abilities. The most effective environment appears to be when the child has a mix of structured tasks, and extended unstructured opportunities to practice trough exploration and play. Care is needed when staff changes are made to ensure that the aims and ongoing programme are maintained. Novel tools and techniques are at particular risk to disruption due to support team changes.

System design

The Smart Wheelchair itself is flexible and robust. Future development should concentrate on enhanced tools for transition in more complex environments beyond school, and into improved integration with other aids. Specific attention is needed to enhance collision sensor life.

Supply, support and service

There is a market for Smart Wheelchairs, but it is complex. To be effective, supply, training, assessment, seat and control tailoring, and long term support must all reflect the unique nature of each chair and user, and the developmental stage they have reached. Over the product life, support costs will be far greater than hardware costs. Such a situation is common in other tailorable systems (such as commercial computer systems), but rarely understood in the context of mobility systems, and difficult to put into place under current Health Service and Educational provision. A possible strategy for service provision would be to build on and extend the expertise of existing regional centres, including augmentative communication centres, supporting this extension through initial training, assessment packs and loans.

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