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Improving training for sensory augmentation using the science of expertise

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Abstract

Sensory substitution and augmentation devices (SSADs) allow users to perceive information about their environment that is usually beyond their sensory capabilities. Despite an extensive history, SSADs are arguably not used to their fullest, both as assistive technology for people with sensory impairment or as research tools in the psychology and neuroscience of sensory perception. Studies of the non-use of other assistive technologies suggest one factor is the balance of benefits gained against the costs incurred. We argue that improving the learning experience would improve this balance, suggest three ways in which it can be improved by leveraging existing cognitive science findings on expertise and skill development, and acknowledge limitations and relevant concerns. We encourage the systematic evaluation of learning programs, and suggest that a more effective learning process for SSADs could reduce the barrier to uptake and allow users to reach higher levels of overall capacity.

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1. Introduction

Sensory substitution and augmentation devices (SSADs) provide perception beyond a user's normal sensory capabilities by compensating for the loss of sensory function or by providing additional information not available to existing senses. They were initially described as merely translating one sensory property of the world into another - 'sensory substitution' (Bach-Y-Rita et al., 1969), but recently the view has been advanced that SSADs provide novel sensory experiences that should be thought of in terms of function and purpose, rather than compared with existing experience - 'sensory augmentation' (Auvray & Myin, 2009; McGann, 2010; Stafford et al., 2011).

SSADs have the potential to be hugely useful in research and in use by the wider public. As a research tool they provide insight into the cognitive and neural processes behind the development and experience of sensory perception and sensorimotor learning (Levy-Tzedek et al., 2012; Ortiz et al., 2011; Stiles & Shimojo, 2015; Maidenbaum et al., 2016; Ward & Meijer, 2010). They also have potential as assistive technology - aiding people with sensory impairment as a result of injury or disability, or providing assistance to people working in poor environmental conditions (Auvray et al., 2007; Bertram et al., 2013; Maidenbaum et al., 2014). Thanks to the growth in the computing power and reduction in size and cost of smartphones and other technology, there has been a dramatic increase in what is possible from a practical and portable, a trend exemplified by the vOICe device (Auvray et al., 2007; Ward & Meijer, 2010). However, despite the potential benefits of SSADs, their full potential remains unrealised: SSADs are not as widely used as more familiar, yet more rudimentary assistive technology, such as the white cane (Loomis, 2010), and while their use as a research tool is flourishing, there are many further opportunities.

Over 40 years have passed since the first SSAD offered the possibility of restoring vision, there has been little penetration of SSADs into the assistive technology market. Over ten years ago, Lenay and colleagues noted that Bach-y-Rita's prediction that SSADs would revolutionise assistive technology re-

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mained unfulfilled (Lenay et al., 1991). That prediction is arguably still unfulfilled. This raises the question: How can we work to help SSADs fulfil their potential?

Underuse is not a problem that is unique to SSADs. SSADs can be considered a subset of the wider category of assistive technology. Although there is an increase in the adoption of assistive technology, a substantial proportion of devices go unused or are later abandoned (Phillips & Zhao, 1993). Assistive technology programs can involve large upfront costs of time, effort, and money, on the part of both the patient and the technology provider (Andrich & Carricciolo, 2007). If these benefits are not realised, then the investments of provider and user are wasted. It is therefore in the interests of both the provider and the recipient to ensure that devices are suitable for their task and properly supported.

The factors underlying rejection and abandonment of traditional assistive technology have been a focus of previous study, and these factors may inform why SSADs are not more widely used. Understanding why a piece of assistive technology is used or not involves assessment of the technology, its capabilities, and how well it performs, but also assessing the needs the user and their attitudes toward the technology (Phillips & Zhao, 1993). Surveys of assistive technology users has revealed that many of the factors relate to balancing the benefits gained by using a device against the cost of time, money and effort invested in learning to use it (Phillips & Zhao, 1993; Batavia & Hammer, 1990). Improving the efficiency of learning to use an SSAD is one way to improve this balance and make their use as an assistive technology and a research tool more appealing. We suggest that that the contribution of SSADs to cognitive science as a research tool can be reciprocated by applying existing knowledge from cognitive science to improve the process of learning to use SSADs.

Provision of support and training was identified as a factor in the abandonment of traditional assistive technology (Phillips & Zhao, 1993; Batavia & Hammer, 1990) and it has been suggested as a factor in improving SSAD use (Elli et al., 2014; Maidenbaum et al., 2014). In the present paper, following a summary of the applications of SSADs and the reasons why they may be rejected, we suggest how the findings of cognitive science can be leveraged to improve the process of learning to use an SSAD. We begin with how the science of expertise can be used to analyse the behaviour of existing practitioners and used to guide training. We then discuss how training programs might be improved. We first address instructed training, including a review of the current approach to training in the SSAD literature, then go on to highlight other approaches to improving training as well as routes to developing proficiency that do not focus on direct instruction, and finally draw attention to some of the limitations and drawbacks of training. We conclude by touching on how the improving the design of SSADs can be used as an alternative method to improve learning.

2. SSADs as research tools and assistive technology

Paul Bach-y-Rita developed the Tactile Visual Substitution System, often regarded as one of the earliest sensory substitution and augmentation device (SSAD) "as a practical aid for the blind and as a means of studying the processing of afferent information in the central nervous system" (Bach-Y-Rita et al., 1969), and SSADs today still represent an opportunity to assist individuals with sensory impairment and to study sensory processing. SSADs typically take parameters from one sensory modality, recode it, and present it in another modality. In the case of the vOICe (Auvray et al., 2007), one of the most commonly used SSADs, an image taken from a camera is encoded as sound. Each pixel is encoded as a sinusoidal tone, where the vertical location of the pixel determines the pitch of the tone, its luminance determines the volume. To represent the horizontal location, the vOICe sweeps across the image from left to right, playing each vertical row of pixels in sequence and panning from left audio channel to the right.

Because SSADs often substitute input in one sensory modality for another, they are commonly referred to as sensory substitution devices (SSDs). However, it has been suggested that the experience provided should be considered as neither that of the substituted sense or the substituting sense, but instead as a distinct sensory experience that is better understood as a way of interacting with the world (Auvray & Myin, 2009; McGann, 2010; Stiles & Shimojo, 2015) Further, some devices do not substitute, but instead provide information that is not naturally available to the existing senses, such as indicating the direction of north (Nagel et al., 2005; Kärcher et al., 2012).Therefore the term 'sensory substitution device' can be extended to 'sensory substitution and augmentation device' (Auvray & Myin, 2009; Stafford et al., 2011; Bertram et al., 2013)).

Users are not only able to use SSADs to interact with the world, but have also reported phenomenological sensory experiences. This has been reported by users with extensive experience of the device (Ward & Meijer, 2010), but also by users who had undergone just three months of training (Ortiz et al., 2011). Whether there are particular experiences with an SSAD that could lead to the development of conscious experience and whether there are individual differences in the likelihood of developing them would be a rich research topic within sensory perception. Input from SSADs can drive subcortically supported behaviour such as visual saccades in the absence of conscious understanding (Wright et al., 2012), but is susceptible to top-down conscious influence (Murphy et al., 2016). As experience with a device progresses, processing the stimuli involves areas of cortex involved in higher level feature processing and identification (Striem-Amit et al., 2012a; Striem-Amit & Amedi, 2014). SSAD have been suggested as a controlled method of studying cross-modal plasticity following sensory impairment and a potential biomarker for adaptability to more invasive vision restoration technologies (Nau et al., 2015a).

As assistive technology, modern SSADs are applied to activities of daily life such as reading, object recognition, and navigation of the environment (Striem-Amit et al., 2012a; Maidenbaum et al., 2016; Nau et al., 2015b). A substantial number of SSADs focus on providing visual information, and SSADs have been presented as an alternative to retinal implants as a method for restoring visual function (Striem-Amit et al., 2012b). Retinal implants involve inserting an electrode array that stimulates the retina according to the luminance of a detected scene, in a similar way to SSADs translating a scene; the stimulation produces phosphenes, and the experience can be used to navigate (for a review of the progress of retinal implants see Dagnelie (2012)). Implants can be expensive (Vaidya et al., 2014), and due to the risk of additional damage, invasive implants are typically used in extreme cases of impairment (Striem-Amit et al., 2012b). In contrast, SSADs can be used regardless of aetiology with little risk. Despite their potential benefit, SSADs are rarely used outside of experimental settings (Loomis, 2010; Maidenbaum et al., 2014). In the following section, we examine research into the non-use and abandonment of traditional assistive technology and SSADs.

3. Use and non-use of assistive technology

The factors underlying rejection and abandonment of traditional assistive technology have been a focus of previous study, and these factors may inform why SSADs are not more widely used. Phillips & Zhao (1993) classified the study of device abandonment into three areas of study: assessment of the characteristics of a device such as how reliable or cost effective it is, assessment of the personal characteristics of users such as their attitudes towards technology, and utilization surveys, where the rates of abandonment of various devices or populations are tracked over time. Phillips & Zhao (1993) conducted large scale assessment across many patient groups to assess user priorities and to measure how those priorities predicted the abandonment of the assistive technology they were using. Four factors were found to be associated with increased abandonment rates - a lack of consideration of user opinion in device selection, poor device performance, changes in user needs, and easy device procurement (i.e. devices that were more readily obtainable were more readily abandoned) (Phillips & Zhao, 1993). Other research has found that users value device performance, particularly how the device meets expectations of performance, reliability, durability, comfort, safety and ease of use (Batavia & Hammer, 1990; Riemer-Reiss & Wacker, 2000). Several of the factors highlighted from research into traditional assistive technology been repeated by reviews focusing on SSADs, along with some that are specific to SSADs: lack of availability, lack of awareness of their existence, concerns about their appearance, cost, difficulty in setting up, and the potential to mask important auditory cues in life (Maidenbaum et al., 2014; Elli et al., 2014). Some of these priorities have been addressed by SSAD researchers: to ensure that the device does not fall short of expected performance due to high expectations, Nau and colleagues begin their training program with an explanation of the capabilities and limits of the device (Nau et al., 2015b), and to improve ease of use, some groups have examined how intuitive the encoding of information is intuitive and easy to understand (Hamilton-Fletcher et al., 2016).

This research into abandonment also highlights the importance of focusing on the user involving them in device decisions and considering abandonment as a problem with how to match a device matches to a user rather getting users to accept the 'right' device (Batavia & Hammer, 1990; Riemer-Reiss & Wacker, 2000). Despite their experience of working with users of assistive devices, the initial list of priorities developed by Batavia & Hammer (1990) was added to by the users, demonstrating the benefits of involving users in the development process regardless of experience. Users also considered whether the device was acceptable on a more personal level whether it was embarrassing to use or wear, and whether the user could customise the device by selecting from options. (Riemer-Reiss & Wacker, 2000). Further, Hocking (1999) highlights the importance of self-identity - whether an individual identifies as being disabled - as an influence on whether an individual would want to a disability aid. These are important issues to consider when bringing an SSAD to market as an assistive device.

The present paper focuses on the process of learning to use an SSAD as a factor in the user experience - through instructional training and through independent learning. The lack of professional support, adequate training the absence of follow-up training in their own home has been identified as a factor in device underuse, especially when the users environment or physical condition changes (Riemer-Reiss & Wacker, 2000; Hocking, 1999; Batavia & Hammer, 1990). The importance of training has been echoed by reviews of the underuse of SSADs, with the suggestion that the creation of ordered training plans would enhance the field (Maidenbaum et al., 2014; Elli et al., 2014). Support in training may be more important for SSADs than for other forms of assistive technology - Nau et al. (2015b) compares the extensive rehabilitation process to that of a hand transplant patient. Device abandonment could be reduced by multidisciplinary interventions, which cognitive scientists could play a part in (Verza et al., 2006).

With the increasing use of SSADs as a tool in cognitive science, we encourage reciprocration by applying the knowledge from cognitive science to systematically evaluating teaching and learning to help develop effective and efficient programs. Improving learning and support for SSADs has two main benefits for patients. First, many of the reasons for abandonment are about whether the investment of time, money, and effort is worth the benefits of increased functionality and independence. Helping users reach a level of proficiency with less training reduces the time investment cost. Helping users reach a higher level of proficiency may reduce the perceived effort. Second, improving introductory training may help users to thoroughly test devices before selection the majority of devices are abandoned in the first year, and the ability to trial a device was associated with its later use (Phillips & Zhao, 1993; Riemer-Reiss & Wacker, 2000). Developing effective introductory training programs could help by helping users to become familiar with equipment much quicker and get a better sense of its benefits. However, while training is an important factor, we should also consider how to learn from and perhaps make use of learning that occurs independent of instructional training. The possibilities of this kind of self-directed exploration can be seen in individuals who have become expert users of SSADs through using them extensively in their daily lives (Ward & Meijer, 2010). The following section addresses in more depth how the learning process may be improved.

4. Training and learning for SSADs

The remainder of this paper addresses ways in which the learning process can be improved, focusing on three areas. The first is in studying existing users of SSADs. We suggest how the principles of the study of expertise could be applied to the behaviour of existing users, and how the findings could inform future training programs. The second area of study is the training programs themselves. We review the training provided in the SSAD literature, which demonstrates a variety of approaches, and offer insights from cognitive science research that may contribute to the development of future training. We also address the limitations and downsides of instructional training as a means to improve performance and present approaches to improving performance that do not focus on structured training. We conclude with a brief discussion on how SSADs can be better designed to make them easier to use, thereby reducing the need for training.

4.1. Applying the study of expertise to SSAD users

To guide the process of improving SSAD training, we suggest drawing on the cognitive science of expertise. After sufficient experience and training with any device, an individual may become expert in its use performing fluidly and without conscious monitoring. This kind of effortless performance is the ideal user experience for those using SSADs as assistive technology. As not every user develops expertise, we might investigate what differentiate users who develop expertise from those who don't, and whether other users can use this information to become experts themselves. The expert performance approach (Ericsson & Charness (1994), for a review see Ericsson et al. (2006)) attempts to explain how experts achieve superior performance in domain specific tasks, with the aim of both understanding expertise and producing it in novices. The approach examines the acquisition of the complex skills and adaptations that enable experts to perform specific tasks at a higher level. Examining these skills allows the key behaviours that produce expertise to be identified and new users to be trained in those behaviours.

The first step is finding an appropriate and efficient task specific measure of expertise. For example, the chess is a complex game requiring the mastery of many abilities, but the skill level of a chess player can be determined from their ability to choose the best next move when presented with a board position taken from the middle of a high-level game (de Groot, 1978). The next step is to identify which of those behaviours are causally related to improved performance. For example, the performance of goalkeepers in judging kick direction is improved by attending to particular postural characteristics and body angles (Williams et al., 2002). Relevant aspects of performance can be identified by techniques such as recording or tracking the behaviour of experts (Williams et al., 2002), recording the movement of their eyes (Reingold et al., 2001) or SSAD equivalent, or by process-tracing techniques such as think-aloud reports (Ericsson, 2006). When identifying the essential components of performing a task with an SSAD, we should be wary of relying on our own preconceptions of SSAD use, particularly those for use by people with sensory impairment. In a review of sensory substitution, Lenay and colleagues warn that it would be vain and pretentious to imagine that sighted persons could know, in advance, the best way of learning how to use a sensory device (Lenay et al., 1991). Using a device extensively provides insight into how a device is used that is not apparent from the outside, which could suggest components of skills to focus training on. One model of expertise suggests that, in general, expert task performance differs from novices in several ways: experts draw upon a wider body of knowledge, but also differs from novices by recognising and focusing on relevant information, adapting to the situation rather than following rigid rules, performing without monitored awareness, and making decisions intuitively rather than analytically (Dreyfus & Dreyfus, 1980). Once identified, the aspects of behaviour that characterise expert performance can be used as the basis for training to help novices improve their performance by having novices model expert behaviour (Farrow et al., 1998; Smeeton et al., 2005) or modify their attentional strategies (Fadde, 2006).

However, it should be noted that while training is likely to help users improve their skills, it is not essential for proficiency. This is certainly the case for traditional assistive technology - for example in a survey of 139 users of assistive technology recruited from postsecondary institutions, Sharpe et al. (2005) reported that 74% had taught themselves, and only 3% had been taught to use their device by disability support personnel. Some existing expert SSAD users have also developed their abilities through independent study. One experienced user of the vOICe, a woman named PF, initially learned to interpret the soundscapes by placing items on a scanner and repeatedly listening to their auditory representation, and another, CC, also taught themselves to understand the auditory output of the vOICe. Through extensive use, CC and PF's experience improved to include depth perception and perception of smooth movement despite the 1 Hz refresh rate of the vOICe display (Ward & Meijer, 2010). However, this was a slow and laborious process, and these case studies may not represent the wider population of SSAD users. While some users are able to achieve competence and even skilled performance entirely through self-taught means, a well-refined training program may help a larger group of users achieve at least a basic level of competence with less effort.

This approach of identifying features of expert behaviour and training novices to exploit these features to reach expertise assumes that the primary difference between experts and non-experts is that experts have been provided with or have discovered the skills needed to reach high levels of performance. However, the success of experts may also rest on factors not captured by behavioural analysis, such as personal experience - prior musical experience has been shown to correlate with acuity when using the vOICe device (Haigh et al., 2013).

Another factor may be motivation. PF and CC's experience of teaching themselves to use the vOICe was a long process (Ward & Meijer, 2010) and other potential users may be unwilling to invest such effort. Thus investigators might also consider motivation as a priority for designing training schemes, and may wish to sacrifice approaches that produce larger increases in performance in favour of those that keep participants engaged. This issue is covered in more depth along with other limitations on training later in this paper.

Applying the expert performance approach to SSAD use is a potentially rich source of investigation. The approach may be initially limited by the small number of users of SSADs that might be considered experts. The small number of experts means they are difficult to recruit, that it will be harder to identify a common ability could be used to define expert performance, and that it will be difficult to generalise from information acquired from some of the techniques mentioned above that produce more variable data, such as process-tracing. However, the present lack of expert SSAD users should not discourage investigation of expert performance; instead, it should motivate research into producing more experts.

4.2. Training and non-training approaches to improving performance

We suggest that the cost of using an SSAD as a research tool or as an assistive device could be reduced by developing effective and efficient training programs, and we encourage the evaluation of training programs through systematic comparison. The importance of support in learning to use an SSAD has been echoed by reviews of the underuse of SSADs, which suggest that the creation of ordered training plans would enhance the field (Maidenbaum et al., 2014; Elli et al., 2014).

Several groups are making progress on developing tools and experience that would enable learning in SSADs to be properly assessed. Poirier et al. (2006) established a performance baseline for "minimalist training" - participants were asked to identify pictures from the soundscapes produced by an SSAD, without even an explanation of how the soundscapes were produced. Having this measure of baseline performance from trial and error learning is useful when evaluating training - some of the studies mentioned below assess the effect of training by comparing post-training performance to pre-training performance. This does not separate out the influence of the training from effect of merely gaining experience of using the device. Nau and colleagues have developed an extensive training program that begins with an intensive two week training course, after which the users take the device home to use in their everyday life (Nau et al., 2015b). Users are contacted on a regular basis to encourage practice with the device, and participants in studies are required to use the device for at least 300 minutes per month. The training itself progresses from the basic elements of perception to complex tasks, moving from familiarisation to identifying basic shapes, then to navigation, and finally development of specific skills relevant to the individual. The protocol has been tuned in response to participant progress and feedback. The program is a remarkable undertaking, developed from their experience of working with users of assistive technology. We hope that the program will continue to be refined and tested, and general principles established so that similar programs could be developed for other devices and user groups. Nau and colleagues have also published details of the standardised obstacle course that is used to test participant performance (Nau et al., 2014). Along with the virtual 3D environments used by Maidenbaum and colleagues (Maidenbaum et al., 2016), these are useful tools to train users of SSADs, allow them to explore and experiment in controlled environments, and to test their performance.

Here, we assess current practice and suggests how principles developed from research into skill learning can be leveraged to contribute to SSAD research, while acknowledging factors that could constrain the use of an ideal training scheme. It should be noted that instructional training is not the only way for users to learn to use an SSAD, and that exploration and experimentation plays a role in learning many skills. Further, consideration must be made of whether learning programs are generally suitable, or whether they are only appropriate for certain patient groups. We conclude this section by addressing the limitations and downsides of training, other approaches to improving learning programs, including gamification, self-directed exploration, and how motivation can play a role in improving the learning experience and through it the use of SSADs.

4.2.1. Training in the SSAD literature

In the present section, we review the training provided in the SSAD literature and offer insights from cognitive science research on how the training might be developed. We focus on four fundamental features of instructional training that have been selected as they are some of the strongest influences on the success of a training strategy in other domains, so their optimisation is likely to produce the greatest benefit for SSAD training, however, this should be verified through systematic evaluation. A more immediate benefit is that they can be readily identified in the training schemes used in existing SSAD literature. Identifying existing practice to establish a benchmark is a necessary first step in evaluating future training schemes. These features effectively illustrate the variation in approaches to training participants, however, a great deal of the variation is likely due to the use of a range of SSADs, some of which may require more or less training than others. Our reviewing the variety of approaches used is not meant to suggest that there is a single ideal training scheme for all SSADs, but rather to demonstrate that there are many potential approaches that have not been thoroughly evaluated. Further, the training provided in a given study is likely to be shaped by experimental and practical concerns.

The four features we addressed here are:

1. The total teaching duration — the most basic measure; simply the amount of training.
2. Session duration and interval — that is, how the total amount of training is broken up into sessions, and how far apart the sessions are spaced.
3. Feedback — how often feedback is provided to the user and the content of feedback; whether it is a measure of performance or results, and whether the results are a binary success/fail outcome, or a more quantitative measure.
4. The similarity of training to end use — the content of the training tasks. For example, whether users are explicitly trained on the task they will be tested on, or training in a general ability that can be generalised to a class of tasks.

Total teaching duration. The amount of teaching is perhaps the simplest and most immediate decision when creating a teaching scheme. Examining SSADs studies reveals wildly differing training durations, from 25 minutes of basic tasks (Levy-Tzedek et al., 2012), to 12 months of intensive training (Robinson et al., 2009). This variation suggests a lack of success in determining the correct cost-benefit balance of training time. There are factors that might influence an appropriate duration; for example, the complexity of device output may be an influencing factor in the length of time needed for users to pick up the basics of the device, or to develop a fuller understanding of its capabilities. Isolating objects from the background and identifying them in the output provided by visual to auditory and visual to tactile SSADs may involve extensive training (Striem-Amit et al., 2012a; Nau et al., 2015b; Lee et al., 2014). In contrast, when the stimulus is more simple, e.g. a two dimensional representation of deviation from vertical, users can learn to interpret this device within minutes (Wood et al., 2009).

However, this tendency for longer training with more complex devices and tasks is not a consistent trend. Although a few basic training tasks might be sufficient to use the BrainPort device (Wood et al., 2009), other groups trained participants with the device for three hours or more (Polat & Uneri, 2010; Uneri & Polat, 2009; Barros et al., 2010). Likewise, while a few hours training or more (Arno et al., 1999; Auvray et al., 2007) might be considered necessary for even basic navigational tasks with more complex devices, some studies provided participants with little or no familiarisation before testing (Brown et al., 2011).

Perhaps a more relevant factor in the choice of training length is the goal of the training, or of the experiment as a whole. Short training sessions were chosen in studies where the intention was merely familiarise the participants with the device and the sensation before a simple task, before tracking how participants acclimatised to the device over a series of tasks (Daz et al., 2012; Levy-Tzedek et al., 2012), or when intentionally studying the effects of a minimal amount of training (Murphy et al., 2016). In contrast, longer training schemes are found in studies where the focus is the development of expert abilities, or the extent to which the user internalises the stimuli provided by the device, (Auvray et al., 2007; Kärcher et al., 2012) or where the intention was to produce effects that would persist after using the device (Robinson et al., 2009).

Practical considerations may also influence the choice of training length, regardless of device or task. The time that participants and experimenters are available, the length of a grant that funds a body of research, or the balance of training few participants intensely versus many participants to a lesser extent are all practical considerations that a researcher must face. We acknowledge that these are often stronger determining factors than what might be the ideal amount of training to provide to participants. However, we encourage researchers to report if the design of their experiment was subject to these sorts of constraints, so that other researchers can take this into account when making their own decisions.

There is an unseized opportunity to systematically evaluate aspects of successful training schemes, even aspects as basic as total training length. Misjudgement of even such a basic aspect has important implications underestimating the amount of training means that the results will underestimate participants true capabilities, overestimating the amount would mean wasted time and effort on the part of the experimenters and participants. In many cases, the benefit of training is assessed by comparing post-training performance to pre-training performance, or to the performance of naive users, without separating the benefit of training from the benefit of experience with the device. Some groups have assessed the benefit of experience by comparing users with untrained experience to naive users (Poirier et al., 2006; Proulx et al., 2008). We encourage similar groups be included in future work to assess the benefit of training above and beyond experience. Close agreement between studies should not be taken as sufficient evidence on which to make a decision: several research groups may have chosen a similar amount of total training time, but how has that consensus been reached? It may have been the result of later publications following the intuitively appealing but unfounded decision of early studies. Alternatively, it may have been the result of independent decisions, all based on an intuition of what seems about right. Neither situation guarantees that the amount of training is necessary or sufficient for the task at hand. Although practice makes perfect, perfection cannot drive decisions about training, as with greater time spent practising produces diminishing returns (Crossman, 1959). An effective and efficient training scheme must therefore balance benefits from more time spent learning against the cost of investing that time.

Session duration and interval. After deciding on the total length of the training, the next step is whether to divide up training into sessions, how long the sessions should be, and how far apart those sessions should be spaced. Many studies have demonstrated the substantial and robust benefits of dividing up training. When the total amount of time is held constant, two or more opportunities to learn a task are more beneficial than a single opportunity the distributed practice effect (for reviews, see Cepeda et al. (2006); Dempster (1989); Donovan & Radosevich (1999); Stafford & Dewar (2014)). Distributing learning improves not only the quantity, but also the quality of learning. The break between distributed practice sessions gives learners the opportunity to consolidate what they know, and to use new strategies based on knowledge gained from previous sessions. Distributed practice benefits learning of declarative knowledge (e.g. Cepeda et al. (2009), for a review see Cepeda et al. (2006)), and provides benefits some aspects of sensorimotor learning (Savion-Lemieux & Penhune, 2010), but it can also benefit tasks that we may expect spacing of sessions to hinder, such as inductive reasoning. Although inductive reasoning requires underlying common rules to be extracted by comparing situations, which we might expect to be hindered by being separated out, performance can be improved by distributed practice (Kornell & Bjork, 2008).

Regarding session length, practice session of around an hour at a time is reported in expert performers (Ericsson, 2006). In several SSAD studies, total teaching lasted less than an hour (Levy-Tzedek et al., 2012; Wood et al., 2009; Lee et al., 2012; Daz et al., 2012). In studies where training lasted longer, sessions often followed this hour guideline. Some studies deviated from this trend, with short sessions of around 20 minutes for the BrainPort device (Polat & Uneri, 2010; Uneri & Polat, 2009; Barros et al., 2010), or session of over an hour for the vOICe visual to auditory SSAD (Striem-Amit et al., 2012a; Auvray et al., 2007) and the BrainPort visual to tactile SSAD (Nau et al., 2015b; Lee et al., 2014). This may be because longer sessions are unnecessary for simpler devices, but are viable for training that involves a range of different tasks that may maintain users interest; navigating, identifying and discriminating a range of different stimuli, and so sessions of an hour or longer are used.

The effectiveness of distributed practice is influenced by the gap between sessions. Further, the most effective gap length is related to the delay between the last session and any tests of performance. Where the delay between the final session and the test is around one day, inter-session gaps of one day are more effective than shorter gaps (see Cepeda et al. (2006)). The effective gap duration may be longer if the learnt material is to be retained for months (Cepeda et al., 2009) or even years (Bahrick & Phelps, 1987; Bahrick et al., 1993).

Again, practical considerations such as participant availability may be of greater concern a long series of sessions may be more practical for participants who are being taught to use a device as part of a clinical appointment, but less suitable for volunteers, who might drop out over the course of an extensive training scheme. This is reflected in two groups who use the BrainPort vestibular-electrotactile SSAD trained participants from different populations, and used different training schedules. Uneri & Polat (2009) used 20 minute sessions separated by 3-4 hours every day for a week, in contrast to Wood et al. (2009) where a single block of more intensive training is used. The participants in Uneri & Polat (2009) are patients with vestibular dysfunction, who might attend a regular check-up, or who may be motivated to attend potentially beneficial treatment sessions, while Wood et al. (2009) are testing healthy adults who may not be available or inclined to attend repeated sessions. Should the design of a training scheme be constrained by other factors, investigation may provide some idea of whether it is significantly less effective compared to an ideal schedule.

Feedback. Feedback is an important aspect of learning any skill. It guides adjustments in behaviour and strategies, and affects motivation, leading to a change in performance. Even the mere promise of future feedback leads people to use strategies that maximise the effectiveness of feedback (Vollmeyer & Rheinberg, 2005). The effectiveness of feedback is influenced by the goals and motives of the learner, the consequences of their performance, and the quality of the feedback (Vollmeyer & Rheinberg, 2005). Good external feedback is essential when an individual is unable to judge their own performance. Judging performance can be difficult when using a novel SSAD, and almost impossible if the user has no other means to perceive their performance for example if the user is sensorily impaired. A particularly vivid illustration of the importance of feedback can be found in a case study of a visually impaired user of the feelSpace navigation device (Kärcher et al., 2012). Throughout training, the user was provided with positive, but non-specific feedback. Although the user enjoyed the experience of using the device, they falsely believed their performance had not improved. To give users a good sense of how they are performing, and consequently encourage them to continue and improve, we should carefully consider the feedback we provide.

There are many options to consider when providing feedback (Schmidt & Lee, 2011). At the broadest level, feedback can be classified as knowledge of results (information about the outcome of a task) or knowledge of performance (information about the process of executing the task). Within each of these types of feedback, the level of description can be varied. At the lowest level, feedback may be merely the success/failure to complete the task or perform the task correctly. More specific measures of how well learner did could be used, which can be comparative (e.g. the ball was thrown too high, or too fast) or quantitative (e.g. a ball was thrown 20 cm away from the target, or twice as fast as necessary). The feedback may be descriptive, as in the previous examples, or prescriptive (e.g. follow through with your arm once you have released the ball). The timing and frequency of feedback should also be considered. Feedback could be provided immediately while it is most relevant, or after a delay once the learner has had time to reflect. In terms of frequency, feedback could be provided continually, or after every nth trial, or every nth failed attempt. When feedback is intermittent, it can be presented as a summary or an average of the preceding trials. This is by no means an exhaustive list of potential options, and it is not intended as such. Instead, it gives some sense of the range of potential varieties of feedback.

Given this broad range of options and the previous lack of consensus on simpler aspects of training such as session length, we might expect to see a similarly broad range of approaches in SSAD literature. Oddly, however, there is instead greater consensus. Excluding studies where the participants are left to explore a device without any guidance, feedback in the majority of SSAD studies consists of an indication of success or failure at a task. This consensus in approaches to feedback could indicate researchers have converged on a best practice; however the lack of evaluation or explanation, as well as the simplicity of the approach suggests that it is merely the default option. The contrast between this under-exploration of different approaches for feedback and the broad range of possibilities summarised above suggests that there may well be more effective ways of providing feedback to SSAD learners.

Providing feedback has long been a topic of research in cognitive science, and so there is a great deal of research that could be drawn on to make suggestions for SSAD researchers. However, the extensive research reveals nuances and apparent conflicts that make it difficult to recommend a best practice here. One common theme that does emerge is that less is generally more. Feedback should be low in detail unless the participants are skilled enough to cope with a large amount of information, and overly detailed feedback can be counter-productive (Linden et al., 1993; Goodman, 1998; Wright et al., 1997). Although experts are capable of making use of detailed information about performance, novices benefit from sparse information (Goodman & Wood, 2004) - which is less overwhelming - and general guidance, which allows the exploration a range of behaviours and develop corrective strategies following poor performance (Goodman & Wood, 2004; Goodman et al., 2011). More detail may be beneficial for learning complex skills. For learning simple skills, knowledge of results may be sufficient; however, a skill with many degrees of freedom may be too difficult for novices to begin to explore effectively. In this case, novices may require from specific prescriptive feedback that suggests modification of causally relevant aspects of performance in order to improve (Kernodle & Carlton, 1992; James, 2012). Providing more detailed knowledge of performance might also be necessary if the method of performance is important to the task; however, the provision of causally relevant feedback requires the experimenter to know what the causally relevant features of performance are. If these features have not been established for a novel SSAD, then feedback may have to be restricted to knowledge of results until relevant features can be established.

The same maxim of less is more also applies to the frequency of feedback. Providing feedback too frequently can lead to the learner relying on feedback to guide performance rather than internalising the skill. Although this may improve initial skill acquisition, it can result in poor retention (Salmoni et al., 1984; Schmidt, 1991). Instead of providing feedback constantly, it can be provided on every nth trial or be faded, with the number of trials between presentations increasing as learning improves (Winstein & Schmidth, 1990). An alternative approach to providing intermittent feedback is to do so only when errors in performance exceed particular thresholds, called bandwidth feedback (Sherwood, 1988; Lee, 1990; Sadowski et al., 2013). Of course, for this approach to be effective, users must be informed about the bandwidth in advance. Another alternative is to provide feedback only when the user requests it (Patterson & Carter, 2010). This allows users to obtain feedback when they need it most (Chiviacowsky & Wulf, 2002), allowing them to focus on receiving feedback on good trials instead of poor trials (Chiviacowsky & Wulf, 2002, 2005), a process that enhances learning (Chiviacowsky & Wulf, 2007). However, as with the detail of feedback, the benefits of low frequency of feedback should be balanced against the complexity of the task, as more complex tasks may benefit from higher feedback frequency (Wulf et al., 1998). For both the detail and frequency of feedback, the challenge is to provide sufficient yet manageable guidance for users to be able to perform the task, while at the same time reducing reliance on external feedback to perform the task. The goal should be to increase reliance on another source of information intrinsic feedback.

Any motor skill has feedback inherent to the performance of the task, which may include kinaesthetic and somatosensory information from the performance of an action, as well as visual and auditory monitoring of performance. This feedback is called intrinsic feedback, in contrast to the feedback discussed earlier, which is provided by an external source in addition to intrinsic feedback, and is known as augmented feedback. SSADs provide a new source of intrinsic feedback, the meaning of which can be explained explicitly, or learned through its congruity with inherent feedback from existing sources produced by the performance of and the results of motor actions. The structure of this learning process can influence its effectiveness. As learning to interpret inherent feedback from an SSAD is effectively learning a new sense, the learning process is perhaps best served by allowing active sensing (Maidenbaum et al., 2014, 2016). Active sensing involves the control of sensory organs (or in this case, sensory devices) that is both purposeful and task specific. Some examples from the SSAD literature illustrate the benefits of these two principles of active sensing. Being able to purposefully control the SSAD allows users to experience the connection between their actions and the output of an SSAD in a way that being passively presented with the same information does not, and results in more effective learning (Daz et al., 2012; Reynolds & Glenney, 2012). The benefit of being able to actively control an SSAD is further affected by whether the control is suited to the specific task. Users of the PSVA, a visual to auditory SSAD, found that learning to locate objects was easier when the camera of the PSVA was head-mounted, while identifying objects was easier when the camera was held in the hand (Kim & Zatorre, 2008). Presumably the location of the camera on the head or in the hand afforded different strategies when controlling the camera that produced different intrinsic feedback, and benefited each task to a greater or lesser extent. Thus, even when no augmented feedback is provided, it is important to structure learning in a way that produces the most effective inherent feedback. If use of an SSAD in different ways affords very different forms of feedback, then an experimenter should carefully consider whether the training provides sufficient experience of the device to perform appropriate real world tasks. This is addressed in more detail in the following section.

Similarity of teaching to use. At the heart of training is the content of the training tasks themselves. The precise content of training tasks will obviously vary from device to device, and situation to situation. Thus to offer practical guidance useful task content, we will address training in terms of its similarity to end use. Similarity can fall on a scale from tasks that are matched to whole tasks in real-world use of the device, to tasks that focus on components of real-world behaviour, to perceptual tasks that are designed to teach rules abstracted from any practical task. The similarity of training to use when training experimental participants may be influenced by the focus of the experiment. Experiments that examine how users develop competence with a novel device might ensure users are merely familiar with the device, while experiments testing performance at a particular task will likely feature training in that task at some point in the training sessions. However, before this point, it may be useful to train users on simpler tasks without complications of a broader context.

Performing a complex task may lead to significant cognitive load and reduced performance, particularly at lower levels of expertise where coping strategies have not been learnt. Several strategies can reduce the cognitive load of a task and improve performance. Each element of a task can be presented in isolation, then combined at a later stage, rather than addressing the whole task at once (Ayres, 2013). Cognitive load can be further reduced by walking the participant through worked examples of performance, rather than asking the participant to perform a task. This allows learners to acquire information, rather than allocating some of their cognitive resources to solving the problem (Rourke & Sweller, 2009). The task of learning to use and SSAD can be simplified still further to the level of perceptual learning training users to interpret the output of the device. Although interpreting the output could be taught through practical situations, users may struggle if they cannot sufficiently distinguish between different values of the output. Training them to do so may be a beneficial first step before the complexities of problem solving are introduced.

An alternative training components of real-world use is to develop complete but simplified versions of real world tasks. Examples of this can be seen in the standardised obstacle course (Nau et al., 2014) and the virtual 3D environments (Maidenbaum et al., 2016) that have been developed. These allow the user to explore the principles of using the device in a simplified manner. Participants generally find them much more enjoyable than basic perceptual training, which can be repetitive (Maidenbaum et al., 2016). The benefits of allowing participants to learn in a self-directed way are addressed in the next section.

4.2.2. Drawbacks and limitations of training

In the present paper we have advocated improving the teaching process as a means of reducing the effort invested in learning to use an SSAD and hopefully improving uptake of SSADs. However, to provide a balanced picture we should address the drawbacks and limitations of training. Affordability is a high priority for users of assistive technology (Phillips & Zhao, 1993; Riemer-Reiss & Wacker, 2000), and the cost of training should be considered as well as the cost of the device. Attending training could also be made more difficult by mobility difficulties or other impairment, creating a barrier for the very people that require support. Alternatives could involve support being provided remotely through telerehabilitation or by designing ways that a user can teach themselves without the involvement of support workers, such as the virtual environments developed by Maidenbaum and colleagues (Maidenbaum et al., 2016).

In the above review, we stated that there was not likely to be one ideal training program for all SSADs given the range of different approaches and levels of complexity. Instead, we suggested that systematic evaluation be used to determine how training could be best shaped for each SSAD or group of similar SSADs. A similar point can be made about the variation between users of SSADs - a training program that is ideal for one population may not be ideal for another. For example, cross-modal correspondences that can be used to make it easier to understand the input-output coding of an auditory-visual or tactile-visual SSAD may only useful to sighted or late-blind participants (Spence & Deroy, 2012). Further, many SSADs will hamper the normal function of the sense through which they present their encoded information. For example, because the vOICe takes a visual image and converts it to a soundscape played through a pair of earphones, it is difficult for the user to hear normally. For many people with an existing sensory impairment, this additional reduction in function may be unacceptable (Maidenbaum et al., 2014; Elli et al., 2014), Finally, the neuroplastic changes or compensatory behavioural changes of an individual with sensory impairment may affect their ability to learn to use an SSAD (Stronks et al., 2015; Murphy et al., 2016; Nau et al., 2015a).

Finally, it is possible that - even if the process of learning to use an SSAD is optimised - they may still not be the 'go to' solution in every situation if it is not worth the effort. An example of this can be found in Phillips & Zhao (1993), who report that one participant abandoned the use of a dressing aid when he returned to work in favour of being dressed by his wife, as the additional independence was not worth the effort it took to use the device. It may be the case that groping blindly is more effective in some situations then making use of an SSAD to see.

4.2.3. Non-training aspects of learning programs

The present paper focuses on the structure and content of training programs as an area where the experience of cognitive science can be applied. However, this kind of direct instruction is by no means the only way in which individuals can learn to use an SSAD self-directed exploration and experimentation with the device can potentially be just as useful as structured training. Further, the most suitable program is not necessarily the one that produces the greatest increase in performance if the tasks involved are arduous or repetitive then the user is not likely to enjoy them. Thus, how the task affect the users motivation must also be considered. We must also consider whether any program can be successfully implemented with the target population we must consider whether the programs are cost efficient, and whether they can be generalised to all patient groups, or whether specific needs must be considered. Finally, improving the procedure for learning to use a device is not the only means to reduce the effort involved the device itself can be made easier to understand and learn through its design. These points are reviewed below.

Some assistive technology can be used with little or no learning. This may be to perform simple tasks, for example we might imagine that a white cane can be used to detect obstacles using a naive strategy. Some SSAD research demonstrates that individuals can learn to interpret the information provided by an SSAD and use it to perform tasks also without extensive training, instead relying on self-directed exploration and experimentation (Poirier et al., 2006; Proulx et al., 2008; Daz et al., 2012; Levy-Tzedek et al., 2012). Perhaps an even more vivid example of expertise independent of training and one also relevant to SSADs is visually impaired individuals who use echolocation to locate objects and navigate the world without any training (Thaler et al., 2011). As has been previously mentioned, some expert SSAD users are primarily self taught or have extended their training through extensive practice at home (Ward & Meijer, 2010; Grant et al., 2016), demonstrating that training is not the only route to profficiency.

Self-directed learning can be an important route to expertise, as users may discover unique strategies that are unknown to training professionals or perhaps particularly suited to their individual needs. Self-teaching may also provide more of a sense of independence, and be more acceptable to those who see mobility training as a challenge to their self-identity. Equally, however, self-directed learners may miss key skills or heuristics provided by training, or may take a long time to reach the same proficiency as a shorter training course. If training is to be used then it should be ensured that it is an effective use of time and appropriate to the trainees. Some aspects of using a device may be difficult to discover through unstructured exploration, and so instruction may be necessary, or at least greatly beneficial. Training can provide additional benefits in the use of traditional assistive technology, even to experienced users (Hersh, 2015). Even the use of hearing aids - an assistive technology that we might assume involves no learning - can be improved by training (Stecker et al., 2006).

Instruction need not come from designated instructors - Elli and colleagues highlight the benefits of collaboration within a community of users. The community has a shared experience from using the same technology, and may exchange strategies and techniques that formal training did not explore (Elli et al., 2014). One of the key beneficial aspects of self-directed exploration is that it is active. Participants learn to use SSADs more successfully when they interact with the world, rather than being passively viewing stimuli (Maidenbaum et al., 2016; Reynolds & Glenney, 2012) and changes in sensory input resulting from self-initiated movement improves participants understanding of SSAD output and their accuracy in interpreting it (Stiles et al., 2015). Participants also report that learning through interacting was more enjoyable, and they were more likely to persist compared to repetitive sensory training (Maidenbaum et al., 2016) This is an important aspect of trying to design learning programs for patient groups that will reduce device abandonment. The benefit of learning through interaction is increased yet further when the interaction can be turned into a game (Reynolds & Glenney, 2012).

4.3. Device design

Although the present paper has focused on how tasks and training might be structured to help an individual to learn a device, an intuitive and easy to use device may also be easier to learn. There are a great many fields that can inform device design, including human-computer interaction, perceptual psychology, and human factors. However, reviewing the principles of all of these fields is beyond the scope of this paper. Instead, some of the work directly related to SSAD design is cited here to provide initial guidance.

Simple devices can be learned quickly: devices such as the EyeCane (Maidenbaum et al., 2014) present a limited amount of information about a focused area, which reduces the amount of information the user has to deal with, and encourages active exploration strategies. Users of the EyeCane quickly learned to navigate a natural environment without substantial training (Maidenbaum et al., 2014). Difficulty in using a device can be reduced by choosing the stimulus dimensions to be optimally distinctive and discriminative (Wright & Ward, 2013), or by simplifying visual information. High detail is not always necessary, and the vOICe can be used to perceive well below native resolution (Brown et al., 2014). Developers of SSADs may shy away from adding additional parameters, worrying that users may be overwhelmed by too much information. However, visual scene segmentation and object recognition is possible at low resolutions, and at low resolution colour information substantially increases scene segmentation and object identification (Torralba, 2009). Thus scaling down the resolution may make the device more usable by reducing complexity, but also make introducing more parameters more viable. Finally, usability may be improved by investigating and using intuitive cross modal correspondences between senses, although designers should bear in mind whether such correspondences are universal (see the section of drawbacks and limitations above)(Hamilton-Fletcher et al., 2016; Spence & Deroy, 2012).

5. Conclusion

A recent review suggested that 'the creation and dissemination of ... longitudinal training programs could significantly enhance the potential outcomes of visual rehabilitation' (Maidenbaum et al., 2014). Training has been highlighted as a factor in influencing whether an individual uses a piece of assistive technology (Phillips & Zhao, 1993; Batavia & Hammer, 1990; Riemer-Reiss & Wacker, 2000) and suggested as an important feature for users of SSADs (Elli et al., 2014). SSADs are increasingly used as a research tool in cognitive science, and we believe that cognitive science can reciprocate by contributing to the development of such training programs. We believe that improving the efficiency of learning to use an SSAD would reduce the effort, time, and money invested by patients and researchers, and potentially makes their use as assistive technology more appealing.

Improving the means through which user attains proficiency can be done through improving training, developing non-training learning, device design. We have selected four features of training schemes that we believe would be productive targets of research aiming to evaluate and improve SSAD training schemes. They were chosen because they are both common to many training schemes in the existing literature, and have been identified in the cognitive science literature as major factors in the effectiveness of training. Although our review of the existing literature revealed little consistency in these factors in current practice for SSAD training, we fully acknowledge that this potentially the result of experimental concerns, the pressing factors of the practicalities of grant periods, the length of patient appointments, or availability of equipment. However, later projects that are unconstrained by such factors may look to prior literature for guidance on experimental design. We would encourage researchers to report if such considerations have influenced the design of their training schemes so that such unnecessary conventions do not develop.

Direct instruction is by no means the only mechanism of learning to use a device. Several studies have highlighted the benefit of self-directed exploration and experimentation in SSAD learning (Maidenbaum et al., 2016; Reynolds & Glenney, 2012). These techniques are both effective, and appear to be more motivating than the repetitive perceptual training that characterises other SSAD training (Maidenbaum et al., 2016). All of these procedures might be made more effective if the device is designed to be intuitive, perhaps by taking advantage of existing cross-modal associations (Hamilton-Fletcher et al., 2016; Spence & Deroy, 2012). Finally, one of the key priorities that influenced whether a piece of assistive technology would be used or not used was whether the user had been involved in the decision making process (Phillips & Zhao, 1993; Batavia & Hammer, 1990; Riemer-Reiss & Wacker, 2000). Developing, providing, and supporting users in the learning of SSADs should be a collaborative process.

Finally, the key aspect of improving the learning process is that alternatives should be systematically evaluated. Evaluating and improving the effectiveness of training may lead to increased use of SSADs as assistive devices and research tools, but also provide greater opportunities for researchers and device developers. We hope that the information presented here provides some inspiration and direction to a field we believe holds great promise.

6. References

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