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The non-disruptive emergence of an ecosystem for 3D Printing — Insights from the hearing aid industry's transition 1989–2008

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ABSTRACT

3D Printing technologies have received extensive attention in recent years, but empirical investigations of how this technology is used for manufacturing are still sparse. More knowledge is also needed regarding how 3D Printing affects the competitive dynamics between firms. This article explores how 3D Printing has been adopted for manufacturing and discusses under what conditions it might influence competition in different industries. Drawing upon data from the global hearing aid industry's adoption of 3D Printing during the period 1989–2008, this paper describes some of the benefits of using the technology, while also pointing out challenges firms encounter in making this transition. The study shows that early adopters were exposed to more technological uncertainty related to choosing printers. All firms encountered operational challenges as 3D Printing required new skill sets, but the technology had little impact on the competitive dynamics of this industry. Drawing upon literature on technological discontinuities, platforms and ecosystems, the paper illustrates and explains why the technology was not disruptive and also discusses how these findings apply to other industries where 3D Printing is currently gaining momentum.

1. Introduction

Digital fabrication technologies have received a lot of attention recently. Having been used for rapid prototyping for a long time (Sachs et al., 1992), this technology (also referred to as additive manufacturing or henceforth 3D Printing) is increasingly also adopted for manufacturing purposes. It has been suggested that 3D Printing will spark a new industrial revolution (The Economist, 2012; Berman, 2012; Gershenfeld, 2012) and that the technology will have disruptive effects in the coming years (Manyika et al., 2013; Petrick and Simpson, 2013), but little empirical evidence has thus far been provided to support such claims.

3D Printer manufacturers are currently growing rapidly and the technology is used for production in several areas, including jewelry, dental implants, orthopedics and components for the automotive and aerospace industries (Hopkinson et al., 2006). As it has only been used for manufacturing in more recent years, studies of how industries transition to using 3D Printing are currently scarce and there is a need for more empirical descriptions of how and why an industry adopts 3D Printing for manufacturing purposes. Such studies can hopefully better inform current discourse on the technology's future impact on manufacturing.

Previous research on innovation has highlighted that technological change frequently results in competitive turbulence and may alter the structure of an industry (Schumpeter, 1936). A growing body of literature has studied how radical technological change affects the dynamics between entrant firms and incumbent firms. Technological transitions can sometimes overthrow entire industries, including the dominant firms (e.g. Sandstrom, 2011). Former photographic film giant Eastman Kodak's bankruptcy can be regarded as one recent illustration of this pattern.

3D Printing is technologically different from other means of manufacturing in the sense that material is added layer by layer rather than subtracted (Karapatis et al., 1998; Mortara et al., 2009). Technologies which require new skills and introduce new performance parameters may at times result in changes in competition (Tushman and Anderson, 1986; Christensen, 1997). 3D Printing is being rapidly adopted in those applications where the need for variation is very high, but has been too costly to accomplish through subtractive manufacturing techniques. In this sense, 3D Printing seems to exhibit some disruptive properties as it introduces new means of creating value (Christensen and Bower, 1996). Despite all the attention around 3D Printing in recent years, it is both theoretically and empirically unclear whether 3D Printing will have any disruptive effects in manufacturing industries more generally.

The purpose of this article is therefore twofold: 1) to provide an empirical illustration of ecosystem emergence in 3D Printing, how and why an industry adopted it for manufacturing purposes and 2) to explore under what circumstances this technology may result in competitive changes and industrial turbulence. This is done through a historical

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case study of how the global hearing aid industry adopted 3D Printing for manufacturing hearing aid shells. Interestingly, the empirical data does not suggest that the introduction of 3D Printing has had any major impact on the competitive landscape of the hearing aid industry. These findings stand in contrast to statements by D'Aveni (2015) about 3D Printing and the hearing aid industry. Drawing upon literature on platforms, ecosystems and technological change, the article explains why that was the case and in doing so, it also seeks to address under what circumstances 3D Printing may have disruptive effects for established industries. The hearing aid industry is a particularly interesting case as it has already transitioned its operations to using 3D Printing. It is therefore possible to perform a retrospective study and explore the results of adoption. While case studies impose constraints on generalization, the findings nevertheless enable a more informed discussion of 3D Printing's potentially disruptive impact on other industries.

The remainder of the paper is organized as follows. The next section provides a theoretical background regarding technological change and ecosystem emergence. Subsequently, the main methods employed for data collection and analysis are presented. The next section describes how hearing aid manufacturers adopted 3D Printing, which is followed by an analysis and a discussion of whether these findings apply to other industries. Towards the end of the article, some managerial implications are provided along with a concluding remark.

2. Literature on technological discontinuities and ecosystems

Innovation frequently happens through a combination of continuous and discontinuous technological change (Utterback, 1994). New technology usually creates extensive uncertainty, experimentation and entry of new firms. Eventually, the industry settles down on a dominant design, which in turn alters the competitive landscape, reduces uncertainty significantly and the industry starts to consolidate. A technological discontinuity can be defined as a punctuated equilibrium and the introduction of an entirely new trajectory. At times, the introduction of a new dominant design related to a technological discontinuity results in the downfall of established firms (Sandstrom, 2011).

Platforms and ecosystems play a crucial role in the emergence of a new technology and a related dominant design. Competition in technology intensive industries increasingly takes place not between firms, but between platforms and ecosystems (Moore, 1993). The emergence of new platforms or ecosystems can have a significant impact on the formation of a dominant design and the competitive outcome of a technological discontinuity. A platform can be defined as a component or subsystem of a technological system where there is substantial interdependence between the subsystem and the larger system, meaning that there is no demand for components when they are disconnected from the larger system (Gawer and Henderson, 2007).

The emergence of a new platform and a related ecosystem may result in competitive turbulence and changes in leadership as such a shift might alter value creation and appropriation, e.g. between component manufacturers and assemblers (Gawer and Cusumano, 2014). Nokia's decline in the transition from feature phones to smartphones can be regarded as one example of such platform emergence resulting in incumbent displacement. To date, there is little research about under what circumstances new platforms and ecosystems result in competitive turbulence, especially in the area of 3D Printing where there is little empirical evidence. Adner (2006) points out a set of challenges related to innovation in an ecosystem. These include interdependence risks, initiative risks related to a certain development project and integration risks of making sure that the solution is adopted by all concerned.

2.1. Technology and incumbent firms

In those cases when a technological discontinuity destroys the value of incumbents' technological competencies, it has been argued that they will be toppled by entrant firms (Tushman and Anderson, 1986). Innovations which distort established product architectures may be equally detrimental for established firms. Technological change on a component level is generally easier to cope with for incumbents (Henderson and Clark, 1990).

A new technology's effect on incumbents' non-technical resources also influences the competitive outcome (Mitchell, 1989, Mitchell, 1992). Drawing upon data from four technological shifts in the typesetter industry, Tripsas (1997) showed that established firms can survive competence-destroying technological change if complementary assets such as specialized equipment and market organizations retain their value.

Another substream of literature on technological discontinuities has explored the role of a firm's environment. Regarding a firm's co-opetitors, i.e. suppliers, partners, alliance partners as a complementary asset, Afuah (2000) argued that technological change which reduces the value of co-opetitors and established relationships will affect incumbents negatively.

Other scholars have studied how incentives differ between entrants and incumbents, arguing that an incumbent's established, profitable markets create an asymmetry of incentives, favoring entrant firms (Christensen and Rosenbloom, 1995). Christensen (1997) suggested that an incumbent's established market controls its resource allocation process. Consequently, established firms struggle to develop technologies which are not initially demanded by their current market. Technologies which underperform but introduce new performance parameters can in this sense be regarded as disruptive. Conversely, technologies that cater to an established firm's current market can be thought of as sustaining. The distinct feature of disruptive technologies is therefore that they are not requested by a firm's customer base. According to Christensen, disruptive technologies are difficult to develop since seemingly rational resource allocation processes tend to favor sustaining technologies.

Summing up the above, a combination of factors determines whether the emergence of a new technology results in the downfall of established firms or not. A new platform or a new ecosystem does not necessarily have to create competitive turbulence. Rather, it depends on how the technology affects competencies, complementary assets, the firms' external environment and their incentive to invest in it. By paying attention to these factors, it is possible to explain how 3D Printing affected the Hearing aid industry and to what extent similar patterns can be expected to occur in other industries where 3D Printing is introduced.

3. Method

The purpose of this article is to describe how 3D Printing has been adopted for manufacturing purposes across an entire industry, while also explaining how the technology has affected the competitive dynamics. In order to do so, an industry where 3D Printing is already in use on a full scale was targeted. The hearing aid industry provided a compelling case as almost the entire industry had transitioned to this technology by 2008-2009. In several other applications, including orthopedics, automotive, dental and aerospace the shift is still taking place. Moreover, the hearing aid industry is well consolidated and six firms together controlled more than 95% of the market in 2012 (Bernstein, 2013), thus making it feasible to study almost the entire industry. In addition to the hearing aid manufacturers, manufacturers of 3D Printers and developers of software and scanners were targeted.

Given that detailed illustrations are needed in order to describe how the hearing aid industry transitioned to 3D Printing, a qualitative case study method was chosen as it enables the kind of rich descriptions needed to address these research questions (Yin, 1994). Case studies result in limited generalizability and are suitable when exploring a that has been scarcely before. As stated previously, there are few studies thus far which have covered how an entire industry has adopted 3D

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Printing for manufacturing purposes and hence, the chosen method is deemed appropriate.

As the purpose is to cover several actors and map how and when they adopted 3D Printing, a focused approach to data collection was employed. By reviewing extensive amounts of secondary data, key individuals who have been in charge of shifting the hearing aid industry towards 3D Printing were targeted. At each of the hearing aid manufacturers, one or several individuals who had been in charge of implementing 3D Printing for manufacturing hearing aid shells were interviewed. Developers of printers, software and scanners were also approached. Here, both directors and people who had been operationally in charge of the hearing aid market were interviewed.

The interview questions concerned when and why each hearing aid manufacturer adopted 3D Printing. Respondents were asked when they first considered using the technology, when they acquired printers and what suppliers they used. They were also asked to describe the main rationale for using 3D Printers as well as the biggest challenges they encountered when implementing it. Interviewees were also asked about how adoption was scaled across their firms, when their entire operations had transitioned into 3D Printing and what the main outcome had been. Questions also concerned whether this technology shift had resulted in any changes in market share among the six incumbent firms and whether any new firms had gained market share. Similar questions were asked to suppliers of printers, software and scanners, thereby enabling triangulation of important events.

In total, 25 interviews were conducted, either over phone or using a video conference platform. Interviews were recorded and transcribed. In addition to the conducted interviews, extensive amounts of secondary data were collected. This data includes annual reports from publicly listed hearing aid manufacturers, marketing material such as case studies and white papers about 3D Printing of hearing aid shells. Data about market share, wholesalers and other industry statistics along with firm specific data in the empirical section come mostly from these sources. The case description below emerged by combining interview material and secondary sources. Less data and information was available regarding one hearing aid manufacturer: Starkey in the United States. The case description below therefore mostly concerns the other five large hearing aid manufacturers.

4. Empirical data

This section describes how 3D Printing was adopted by the hearing aid industry. First, an industry background is provided. This is followed by a brief description of hearing aid shell production. The coming subsections cover how 3D Printing was adopted by the hearing aid industry.

A hearing aid essentially contains the following components: an electronic signal processor, a microphone, a battery and a loudspeaker, which are then placed inside a shell (Masters et al., 2006). Fitting all these components into a very small space has been a key challenge for hearing aid manufacturers over the years. The limited space imposes constraints upon batteries, but also implies that acoustic problems such as feedback from the receiver to the microphone have plagued many products. (Lotz, 1998).

Hearing aids can be classified as either Behind-The-Ear (BTE) or In-The-Ear products (ITE), the latter category being the more expensive one as it has to be customized for each patient. ITEs can in turn be classified as standard ITEs, In-the-canal (ITC) and completely-in-the-canal (CIC) products which are more or less invisible to others. It is possible to customize BTE instruments, but most such work has been done in the ITC/CIC categories (Masters et al., 2006). There are also hybrid products which put the receiver in the canal, but other components behind the ear (RICs). 3D Printing is primarily used for ITE products as these need to be customized to each patient's ear. Besides traditional hearing aids, the Cochlear implant market constitutes a large yet rather separate niche which has not been affected by 3D Printing.

10–11 million hearing aids were sold in 2012 and industry turnover amounted to $5.4 billion in 2012. Europe is the largest market (45%), followed by the United States (29%). Growth has remained moderate yet steady over the last decades at about 5% (Bernstein, 2013).

The Hearing Aid industry can be described as stable and consolidated. It is dominated by six large firms which together control a significant majority of the market (see Table 1). Out of these six players, five are European and three are Danish. Phonak and Oticon are currently the largest hearing aid manufacturers.

Gross margins are generally high in the industry, often well above 60% (GN Resound Annual Report, 2013). Unlike other electronic products, hearing aids have not been subject to steep declines in prices. To the contrary, the average retail price increased by 67% 1994–2000, well above inflation in most Western countries during this period. A well consolidated industry, low bargaining power among end-users and technological advances are some of the reasons why prices have increased over time. The industry has remained R&D intensive, the firms mentioned above spend 5–9% of their turnover on Research and Development.

Hearing aids are sold through a couple of different channels, e.g. retail chains, hospitals and independent dispensers. In 2000, 45% of all hearing aids were sold via audiologists and 23% via hearing aid stores. These are the two main sales channels, but there is considerable variation across countries. In the United States, the hearing aid clinics sector remains fragmented with no single company dominating the market. About 15,000 people are employed in this industry and there are more than 5000 businesses, which indicates that the industry is mostly populated by small independent hearing aid dispensers (IBISWorld, 2013).

Hearing aid manufacturers also control their own sales channels. For instance, a third of Phonak's sales came from their own 2000 retail outlets. Oticon owns 1200 stores which in total accounted for 21% of its turnover in 2012. End-users are generally not conscious about the brands or manufacturers. They rely quite heavily on recommendations from hearing aid dispensers, who in turn are partly controlled by different hearing aid manufacturers. The amount of independent audiologists has declined significantly over the past decade. For example, in 2004, 46% of US hearing aid dispensers were independent, in 2011 this figure had declined to 23%. Moreover, there has been extensive consolidation in the hearing aid industry over the past 15 years, largely driven by Mergers and Acquisitions (M&As) and increased vertical integration (Pyndt and Pedersen, 2006).

4.1. Digital and manual production of hearing aid shells

ITE hearing aids need to be customized to each patient and therefore, the hearing aid shell has to be tailored. It needs to fit tightly in order to avoid feedback that may result in squealing noise inside the ear. Creating such hearing aids used to be a challenging and time consuming process, involving a sequence of activities. First, an audiologist creates a model of the patient's ear canal by injecting silicone. This impression is sent to the hearing aid manufacturer. Highly skilled technicians

Table 1
Changes in market share among the six largest hearing aid manufacturers 2005–2012. Siemens and Starkey have lost market share while Phonak and Oticon have gained share. In total, the industry has become more consolidated as the largest six firms control a larger part of the market (Bernstein, 2013).

Firm	2005	2012	Change, percentage points
Siemens	23%	17%	−6%
Oticon	18%	24%	6%
Phonak	17%	24%	7%
GN ReSound	14%	16%	2%
Starkey	11%	9%	−2%
Widex	9%	9%	0%
Total	92%	99%	7%

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then create the hearing aid shell through a series of manual steps including sculpting, molding and curing. Finally, electronic components are integrated into the shell, it is tested and then delivered to the customer. There were several problems related to this process. First, it was very costly for manufacturers. Second, the technician's work is largely an art and there is room for human error here, resulting in unreliable products. If the user would need a new shell, the entire process above has to be reiterated, with no guarantees of an accurate end result (Masters et al., 2006).

3D Printing removes the time consuming manual labor related to creating the shell. In order to accomplish this, not only printers are needed but also complementary technologies such as 3D scanners and software for three dimensional modeling. Instead of creating a mold, the ear impression is scanned and a digital file is created. This is done either by the audiologist who then sends the file electronically to the manufacturer, or by the manufacturer based upon an impression created by the audiologist. Using advanced 3D modeling software, the electronic file is then converted into a version that can be used as input for the 3D Printer. The 3D Printer now builds a batch of shells and after some post processing such as grinding, electronic components are inserted into the shell which is then sent to the user.

Several different 3D Printing technologies exist (Mortara et al., 2009), Stereolithography (SLA) and Selective Laser Sintering (SLS) are the most important ones for the hearing aid industry. Stereolithography was pioneered by 3D Systems Corporation in the United States in the 1980s. In recent years, 3D Systems has also obtained capabilities related to SLS, primarily by acquiring DTM Corporation. Another form of SLA referred to as Selective Light Modulation is offered by Envisiontec, a firm located both in Germany and the United States. Envisiontec was founded in 2002 and currently holds about 60% of the global market for 3D Printers used in the hearing aid industry. SLS technology has primarily been supplied by DTM Corporation in the United States and by EOS, a firm located in the Munich area in Germany.

When it comes to software and scanners, 3Shape in Copenhagen, Denmark, has become the dominant player controlling virtually the entire hearing aid market. 3Shape offers a complete solution, including various forms of software and scanners. In recent years, 3Shape has focused on the dental industry, providing a similar solution as the one originally developed for the hearing aid industry. Other software suppliers include Geomagic in the United States and Materialise in Belgium.

4.2. Early applications of 3D Printing

The first use of 3D Printing in the hearing aid industry dates back to 1988–1989 when Siemens conducted a feasibility study. A group of engineers investigated whether it would be theoretically possible to use additive manufacturing for making hearing aid shells. The main objective of trying out 3D Printing was to increase controllability and to industrialize the process. As the manual process was based on artisanship, it was difficult to control it and reliability was low. Siemens concluded that 3D Printing was at this point too expensive and did not result in sufficient resolution, while also requiring a lot of post processing. Estimates pointed at capital investments of up to 4–5 million US Dollars, a unit cost of 20–30 dollars and additional processing work of up to 3 h. Siemens therefore left this technology for the coming years and instead focused on improving the manual process, efforts which eventually resulted in a shift from acrylics to a UV-based technology. Challenges related to temperature and humidity could be handled more easily by doing so, but the core problem of controllability remained largely intact.

In 1992, the CEO of family-owned Widex in Denmark, Jan Topholm, patented a process for using 3D Printing for making hearing aid shells. While there were a lot of patents related to using SLA, there were no specific ones for making hearing aid shells. The patent has been described as quite general as it concerned the actual printing of a shell, regardless of which technology is used (SLA or SLS). In the following years, Widex obtained royalties from several of its competitors, about half a dollar for every shell that is produced.

While there had been some discussion at Widex regarding 3D Printing in the 1990s, little had happened as the technology was still immature in many regards. The first steps towards adoption were instead taken by Siemens and Phonak in the late 1990s. Siemens had a background as primarily dominating the BTE category. In the 1990s, the company therefore saw growth opportunities in expanding its presence in the ITE category. Siemens had grown significantly in these years and had grabbed market share in the ITE category, primarily from Starkey who originally pioneered ITEs in the 1970s. In 2000, Siemens' directors were convinced that it would be able to dominate the ITE category by adopting 3D Printing, provided that it entered rapidly and could gain a head start vis-à-vis its competitors. The adoption of 3D Printing was largely a manufacturing driven task, with explicit focus on speed and efficiency. With the original idea to set an industry standard that others would later have to follow, Siemens formed a consortium together with Phonak. One of the motives for this consortium was to reap economies of scale, especially related to software and scanners, which were very expensive. After having worked with Geomagic for a short while, Siemens and Phonak initiated a collaboration with the Belgian firm Materialise. Rather than owning the developed software, Materialise worked as a subcontractor for Siemens and Phonak. Materialise worked closely with craftsmen at both Phonak and Siemens to understand the work process and their demands.

4.3. The first attempts to implement 3D Printing

In 1999, Siemens and Phonak together started to explore different 3D Printing technologies. Stereolithography (SLA) could not offer biocompatible material at this point and had to be rejected. SLS seemed more promising as it used nylon, a biocompatible material that was harder and more robust. It was however not possible to glue and grind SLS shells as the color would change.

In 2000–2001, SLS was cheaper and better than SLA, at least according to both Phonak and Siemens who tried both technologies and decided to go ahead with SLS. As both firms wanted to start with the larger US market, they approached DTM Corporation in Texas, which was the only firm that could supply SLS machines in the United States. In Europe, they interacted with German SLS manufacturer EOS. At EOS, printers had thus far primarily been used for rapid prototyping purposes. Many of the specifications provided by Siemens and Phonak proved important for EOS when developing machines reliable enough for manufacturing purposes.

Six months after Siemens and Phonak decided to go for SLS 3D Systems launched the Viper, an SLA machine which was cheaper, had better resolution and also offered biocompatible material. By then, Siemens had already bought ten SLS machines while Phonak had bought two for the US market.

Technologically, SLS was capable of producing functional hearing aid shells. The color, however, was different. Hearing aid dispensers are perhaps the most important decision makers when it comes to which hearing aids are bought. As the shell looked different, they did not like it. This in combination with the fact that new technology was used created resistance in the marketplace. Moreover, oftentimes, dispensers had to polish, grind and adapt the shell when having received it from the manufacturer. This was not possible with sintered parts, which also generated frustration among dispensers.

As a consequence, the technology experienced a backlash among wholesalers in the United States in 2003. Both Siemens and Phonak later shifted to SLA. Prior to the backlash, GN ReSound had also invested in two SLS systems and 15–20% of GN's shells were produced using SLS at this point. GN ReSound only received a few complaints as the process had not been scaled up entirely.

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4.4. Stereolithography (SLA) and successful adoption

While there had been some discussions at Widex in Denmark regarding 3D Printing in the 1990s, little had happened as the technology was still immature in many regards. In 2001, however, two Danish graduate students named Tais Clausen and Nicholai Deichmann, had developed a prototype of a 3D scanner. They sent two samples of scanned hearing aid shells to the three Danish hearing aid manufacturers (Widex, Oticon and GN ReSound). Widex' CEO Jan Topholm immediately contacted them and asked for a meeting. They signed an agreement, Topholm paid some money up front to Clausen and Deichmann for the development of a scanner. Within a couple of weeks, the students came back with a working prototype in October 2001. Topholm asked them to also develop some software, Clausen and Deichmann now founded 3Shape and initiated development work.

In the meantime, Widex tried both SLS and SLA technology. Whereas Siemens and Phonak started to use SLS, Widex only tested it and chose to wait until biocompatible material for SLA would emerge. The solution came around when Dreve Materials in Germany developed a material suitable for the SLA process. Dreve had been a supplier of material for the manual process of making hearing aid shells. As people at Dreve realized their business might be displaced by 3D Printing, they devoted efforts to developing biocompatible material for SLA which were successfully launched in late 2002.

Still collaborating closely with 3Shape, Widex now started implementing 3D Printing on Iceland and at a few clinics in Denmark, which was followed by the United States in February 2003. The company did not encounter any particular challenges. An important reason for this seems to have been that there was no visual or functional difference between SLA shells and manually created shells.

Having scaled up SLS in 2002–2003, Siemens now went aggressively for SLA and quickly installed 20–35 machines in 9–12 countries around the world in the following years. In comparison to their competitors, Oticon had adapted a more passive strategy. Also being located in Denmark, the firm maintained close relations to Widex and 3Shape in the years 2001–2003 in order to learn more about the technology. It became clear by 2003 that Vipers from 3D Systems was the best choice and Oticon now started to scale up. In 2005, the firm had transitioned most of its operations to using 3D Printers.

4.5. The shift to Selective Light Modulation (SLM)

Having experienced difficulties with SLS, Phonak switched to 3D printers from Envisiontec in 2004–2005, which used a new technology. Selective Light Modulation Printers are based on a UV curable technology and produced shells which looked more like traditional ones in terms of color and material, while also offering more different colors. Also, these printers were significantly smaller and cheaper. SLA machines from 3D Systems used to cost 200 000 euros and prices had now declined to 150,000 euros, which can be compared to Envisiontec's machines priced at 100,000 euros.

GN ReSound had initially explored SLM in 2002 and used it on a limited basis in 2003. GN ReSound scaled up its use of SLM in 2004–2005 and in 2008 about 90% of production had transitioned to 3D Printing.

Other firms such as Widex and Oticon chose to continue using Vipers from 3D Systems instead of Envisiontec's printers. While Envisiontec is cheaper, it is according to Widex not accurate enough. With Vipers, it is possible to completely integrate the shell with the top of the faceplate. Competitors have to first put in the electronics and then glue it, something that makes the product more vulnerable and the process more labor intensive. From the beginning, Widex has only used Vipers at its 41 different sites.

Envisiontec's SLM technology, has along with software and scanners from 3Shape in Denmark become the standard solution for making hearing aid shells. 3Shape currently controls more than 90% of the market for scanners and software while Envisiontec holds a market share around 60%. While 3Shape emerged in a symbiotic relationship with Widex, the company made sure to control its own software as opposed to Materialise who worked as a contractor for Siemens and Phonak. Consequently, 3Shape could scale up and expand and once Materialise were freed from the exclusivity agreement, 3Shape had already captured the majority of the market.

4.6. Adopting 3D Printing: main motives and challenges

Hearing aid manufacturers report several benefits of adopting 3D Printing. Though lower cost in the long term has been pointed out as an important reason, the main rationale has for most firms been related to the fact that it would be possible to make a better end product by using the technology. To most of the studied firms, 3D Printing was a technology that enabled the industrialization of a process that had historically been plagued with quality problems and impossible to standardize. Work that previously took 1 h could in some cases now be done in 5 min. Also, the manual process was associated with a couple of drawbacks: it smelled, created fumes and used a set of liquids that were unpleasant to the person working with it. Additionally, shells could now be stored as electronic files, thereby making it a lot easier to create a replica without making a new impression. Another motive was related to the fact that 3D Printing would make it possible to create more different shapes and ear impressions, thereby creating improved comfort and acoustic fit. In sum, hearing aid manufacturers had clear incentives to adopt 3D Printing. According to Klaus Vaarbroe, who has been responsible for 3D Printing at Widex since 2002, "*there was no reason not to do it*". At the same time, none of the respondents expressed any concern that not adopting 3D Printing would result in a loss of competitive advantage vis-à-vis their competitors.

The biggest anticipated challenge was related to the re-education of staff. The use of software and printers required a new set of skills and all hearing aid manufacturers report that this was the greatest challenge they anticipated. While this shift required effort, several firms state that the change was actually less dramatic than they had expected. At many firms, e.g. Phonak, Widex and Oticon, technicians were quite positive to this change and were keen to learn more about the technology while also getting away from the toxic fumes. Moreover, a large share of the artisan's skill set remained intact. Creating a hearing aid shell not only requires manual skills but also visual skills. It was therefore easier for trained artisans to learn how to use 3D Printers than for non-artisans. Most of the hearing aid manufacturers therefore retained their artisans and retrained them, though in some cases layoffs took place.

4.7. Outcome and impact on competition

The adoption of 3D Printing has both improved quality and productivity. At Widex in Denmark, half the amount of people are now making four times as many shells per unit of time. In France, Widex' investment in 3D Printing was profitable within less than a year. 3D Printing also enabled Widex to create and improve certain features. Shells can now be designed differently, both to create better acoustics and to integrate more electronics into the products. Firms like GN ReSound have recently begun to design products that take advantage of what 3D printers can do. GN ReSound's project director, Russ Schreiner stated in a book chapter that "*Rapid manufacturing machines allow you to produce features that are not possible with conventional molding or casting*" (Raja and Fernandes, 2008, p. 188). While 3D Printing has opened up for a wide range of new opportunities, several respondents report that a lot of potential remains unrealized, something that in retrospective has been expressed as a concern and disappointment.

3D Printing has to an extent driven centralization of manufacturing for several firms, including GN ReSound, Widex and Phonak. At GN ReSound, 3D Printing has also resulted in increased offshoring as files

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can be easily transmitted to e.g. China, modeled and sent back to the hearing aid dispenser.

Being a latecomer seems to have been associated with several advantages, lower cost being the most obvious one. In one comparison, a later adopter had 60 percent lower costs for software and equipment.

According to all respondents, the shift to 3D Printing did not have any major impact on the competitive landscape. While 3D Printing has clearly improved the quality of ITE products, this category of products has still been subject to a steep decline and now only accounts for 25–30% of the market as compared to 70% in the early 2000s.

A couple of other trends have worked against ITEs, the emergence of Receiver-In-The-Canal (RIC) products is arguably one of them. RICs offer a good tradeoff between price and performance, while being less visible than BTEs. The RIC category is growing about 30% annually and those companies which have invested early in these products have benefited extensively.

Changes in market structure have also favored RICs. For dispensers, it is much more expensive to sell custom products as they create a lot of work in terms of fitting the hearing aid, interacting with the manufacturer and also in terms of cleaning the product. With BTEs or RICs, dispensers instead make a quick sale. About 80% of all potential customers want a custom hearing aid but only 10–20% end up buying one as dispensers tend to guide them towards RICs or BTEs.

Dispensers are to a larger extent now either controlled by hearing aid manufacturers or by large retail chains such as Amplifon or Audiomall. Thus, the wholesale channel is to a much larger extent driven by profit motives today and ITEs are less profitable as they require more labor. Moreover, the continued economic crisis that started in 2007–2008 has put pressure on reimbursement schemes and since ITEs are more expensive, this factor has further contributed to the decline of this category.

Phonak's market share has increased from 10% to 24% since 2005 and the firm has toppled Siemens as the leader in the industry. According to the gathered data, this change in leadership is more related to other events than the shift to 3D Printing. Phonak developed a more complete product portfolio, created a common technology platform that enabled economies of scale and also made significant advancements in wireless technology.

The changes that the hearing aid industry has undergone over the past decade are more related to other factors than the shift to 3D Printing. According to all respondents, Siemens' declining market share during the studied time period cannot be attributed to 3D Printing.

5. Analysis and discussion

As stated in the literature review, a technology's impact on incumbent firms can either be analyzed in terms of how it affects the focal firm and its competencies or in terms of how it influences the firm's linkages to the market and the surrounding environment. Table 2 below highlights those factors that explain whether incumbents encounter any difficulties under conditions of technological change and addresses how these apply to the introduction of 3D Printing in the hearing aid industry.

As can be seen in the table above, 3D Printing's impact on those factors that influence the competitive dynamics in a technological transition has been relatively minor. The technology was only partially competence-destroying as the overall product remained the same. This, in combination with the fact that non-technical assets remained intact seems to have prevented entry into the market. The non-technical assets include e.g. brands, extensive sales organizations and manufacturing that apart from the shell production did not change. Moreover, the hearing aid shell is only one component in an overall product architecture that has remained intact. As most of the added value of a hearing aid manufacturer is related to signal processing technologies rather than the shell, the shift to 3D Printing has not resulted in any entry into the market. According to the innovation taxonomy of Henderson and Clark (1990), 3D Printing can therefore be regarded as a component-level innovation and these rarely lead to problems for incumbent firms.

Another factor to consider when addressing the impact of a new technology on incumbent firms is related to whether it is competence-destroying or not for important stakeholders, e.g. suppliers and customers (Afuah and Bahram, 1995). Apart from the wholesale backlash related to the early introduction of SLS, no such effects have been reported. When the industry shifted to SLA machines in 2002–2003, hearing aid dispensers could no longer tell the difference between manually crafted shells and printed shells. The positive outcomes for dispensers in terms of quality improvements and reduced return rates further suggest that customers were not negatively affected in any substantial way.

An important reason for the minor impact on the competitive dynamics might also be related to the availability of the technology. The ecosystem around 3D Printing, e.g. 3D printers, software and scanners were available on the market from quite an early point and hence, one should not expect that it would result in any competitive changes among the dominant players as the technology was accessible to everyone. As stated in the literature review, a platform can be thought of as a subset to a larger technical system (Gawer and Henderson, 2007). In the case of the hearing aid industry, the larger technical system did not change with the emergence of 3D Printing. New platforms might distort value creation and appropriation (Gawer and Cusumano, 2014). It is clear that actors such as 3Shape and Envisiontec started to supply technology and thus created a larger share of the added value compared when hearing aid manufacturers used craftsmen to perform manual labor. As the vast majority of the technical system that makes up a hearing aid remained the same, this shift in value creation and capture did not have any significant impact on the industry, especially bearing in mind that 3D Printing resulted in substantial cost savings and quality improvements on behalf of the manufacturers.

As demonstrated through the examples of GN ReSound and Oticon, firms lagging behind or deliberately adopting a “wait and see” strategy could easily catch up with the first movers, who at times lost

Table 2
A summary of the main factors explaining whether incumbents encounter problems due to technological change.

Firm-related explanations of incumbent problems due to technological change	The hearing aid industry and 3D Printing
Technological competencies are rendered obsolete (Tushman and Anderson, 1986).	Only a small fraction of the technological competencies were lost as the making of a shell is about 10% of the overall manufacturing related to hearing aids and most of the added value is related to signal processing.
A new technology may impose architectural changes that turn current organizational structures into a disadvantage (Henderson and Clark, 1990).	The interrelationship between the hearing aid shell and other parts of the product architecture has remained intact.
A technology might change the value of incumbents' non-technical assets (Tripsas, 1997).	Non-technical assets such as intellectual property, brands and market organizations have not been affected by 3D Printing.
Innovations that are competence-destroying or impose architectural changes for key actors in a firm's environment might be problematic to introduce (Afuah and Bahram, 1995).	SLS had some of these properties as dispensers could not grind or polish the shells in the same way. Once SLA was adopted, however, there was no significant impact on dispensers, or end users.
Established firms struggle to prioritize innovations that are not demanded by their current, profitable market (Christensen and Rosenbloom, 1995)	From an early point, it was clear that the profitable markets of established firms would benefit from 3D printed shells, e.g. through lower cost, better products and a decreased return rate

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momentum due to the technological uncertainty they were exposed to. If special 3D printers had been developed in-house by some hearing aid manufacturers, the technology might have had a larger impact on the competitive landscape. Considering how small part of the end product's value that is actually related to 3D Printing, it is still questionable whether this would have resulted in any major competitive changes. 3D Printing's impact was summarized in the following way by one respondent: "*It's a common process for all manufacturers now*".

It is also clear from the empirical description that incumbent firms had obvious financial incentives to invest in 3D Printing. The technology could lower their cost while also resulting in better products that the hearing aid market demanded. Established firms were therefore highly motivated to invest in this technology, which can be illustrated by the fact that several firms explored 3D Printing in the late 1980s and early 1990s. In this sense, 3D Printing was not a disruptive technology, but rather a sustaining one as there was a clear financial logic in pursuing it (Christensen and Rosenbloom, 1995).

Summarizing the above, 3D Printing has not caused any major competitive changes in the hearing aid industry, neither in terms of new entrants coming into the market nor in terms of changes in market share between the established players. This finding stands in contrast to statements made in a recently published article by D'Aveni (2015, p. 41): "*The U.S. hearing aid industry converted to 100% additive manufacturing in less than 500 days, according to one industry CEO, and not one company that stuck to traditional manufacturing methods survived*". According to both secondary data such as statistics on market share and entry into the industry (see Table 1) as well as all respondents interviewed in this study, 3D Printing did not induce any substantial changes in the competitive landscape as suggested by D'Aveni (2015).

A number of reasons for this lack of disruption have been identified. 3D Printing only concerned one component in a larger technical system that remained intact (Gawer and Henderson, 2007; Henderson and Clark, 1990). Moreover, 3D Printing did not affect the industry structure in terms of enabling new market channels or destroying the value of non-technical assets (Tripsas, 1997). Also, the technology has along with software and scanners been accessible to all firms from an early point. While being exposed to a minor destruction of competencies, incumbent firms succeeded in this transition as they had plenty of financial incentives to do so and therefore, 3D Printing should in this case be regarded as a sustaining rather than disruptive technology (Christensen and Bower, 1996). Moreover, competence destruction was relatively minor in relation to the overall business of hearing aid manufacturers.

5.1. Discussion and managerial implications

Based on the findings above and the theoretical framework sketched in Section 2, one can discuss and hypothesize regarding the impact 3D Printing will have on other industries. Some dental and medical applications might be similar to the hearing aid industry in the sense that 3D Printing is replacing a manual process. Therefore it will arguably result in similar benefits in terms of better control and quality. Another commonality is probably related to competence destruction and the retraining of staff that might be needed. As 3Shape, EOS and other key suppliers of 3D Printing technology entered the dental application after having successfully transitioned the hearing aid industry, we can expect that the events which unfolded in the dental industry were similar with regard to competence renewal and some scholars have suggested that this would be the case (Strub et al., 2006).

The hearing aid industry could be different in the sense that it is highly consolidated. The fact that only six players control the entire market might have contributed to the rapid adoption of 3D Printing in the years 2000–2008. Some respondents at 3D Printer manufacturing firms stated that the dental industry is more fragmented and that the shift might therefore have been slower here.

The empirical section described how an important reason for the lack of disruptive effects was related to the fact that 3D Printing is only a limited part of a larger technical system. Aerospace, automotive and other industrial applications might be similar to the hearing aid industry in the sense that it only affects a few components in a larger technical system which may in many cases remain largely intact. When this is the case, and complementary assets retain their value, the outcome will probably be similar — 3D Printing would be a radical process innovation that has little impact on the competitive dynamics. A third factor contributing to this scenario would be that up until now, 3D printers, software and scanners have been provided by an ecosystem of specialized firms, meaning that turnkey solutions are available on the market for anyone who wishes to purchase them. As long as this is the case, the technology as such may not cause any firm to gain a competitive edge over others as long as 3D Printing is only a platform in a larger technical system.

The case, might, however, be different for consumer products or applications where 3D Printing cannot be regarded as a platform in a larger technical system. When the printed product is also the end product, there are arguably fewer barriers to entry and in such a case, 3D Printing might cause disruptive changes. Complementary assets such as brands could possibly shelter larger firms from such changes. In other settings, one can imagine that complementary assets are indeed affected by 3D Printing, making it unclear how established firms will be affected. Some scholars have argued that the technology will make it difficult to enforce copyright laws in the future and that manufacturing will encounter similar challenges as the music industry when MP3 files became widely available over the internet (Desai and Magliocca, 2013).

As can be seen in the empirical description, hearing aid manufacturers differed in some regards in how they approached 3D Printing. Some firms, e.g. Siemens, had a very clear vision and pursued this opportunity vigorously. Being an early adopter did not imply that Siemens (or Phonak) had transitioned to 3D Printing before any of their competitors. The main reason for this appears to be that the initial technological uncertainty made it difficult to make the right decision concerning what technology to use, which is normally the case when a materially different technology is introduced (Utterback, 1994). Up until late 2002 when biocompatible material emerged for SLA, uncertainty was still high and as a consequence, Siemens and Phonak went down the SLS path for a couple of years. At the same time, several firms stated that a major success factor was the gradual, step-by-step approach enacted.

SLA machines with biocompatible materials, along with software from 3Shape can be regarded as the dominant design (Utterback, 1994) for 3D Printing in the hearing aid industry. Firms scaling up after the emergence of this dominant design such as GN ReSound and Oticon were less exposed to initiative risks, interdependence risks and integration risks (Adner, 2006) as compared to the early movers. They could gradually expand their operations without any backlash in the marketplace. This observation speaks for prudence and firms interested in adopting 3D Printing need to follow the technology closely, develop capabilities to adopt it but avoid scaling up when uncertainty is still too high. It should also be emphasized that these firms made sure to monitor the technology closely prior to the emergence of a dominant design and that they build an absorptive capacity (Cohen and Levinthal, 1990). Having done so, they could scale up their operations and transition to 3D Printing rather swiftly.

6. Conclusion

The purpose of this paper has been to explore how and why 3D Printing is adopted for manufacturing purposes, while also investigating how 3D Printing has affected the competitive dynamics of an industry. In doing so, the paper makes an important empirical contribution as there are few studies mapping how 3D Printing has been adopted on a full scale. Also, this article provides indicative evidence regarding under what circumstances 3D Printing might have disruptive effects for established firms.

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All the big six hearing aid manufacturers adopted 3D Printing during the period 2000–2006. While they approached the technology in slightly different ways, the main rationale has been quite similar across these firms. The aim was to industrialize production of hearing aid shells, a process that had previously been unreliable, labor intensive and expensive. By replacing this process with 3D Printing, hearing aid manufacturers could not only lower their cost significantly, they could also improve quality and decrease return rates. Also, the technology enabled them to create replicas easily as all scanned impressions are stored electronically. They thus had plenty of incentives to pursue 3D Printing and this is probably one of the main explanations to why adoption was rather swift and uniform across the industry.

When adopting 3D Printing, hearing aid manufacturers encountered both operational and technological challenges. All of them had operational challenges, primarily related to the fact that technicians had to be retrained in order to use software and printers. In this sense, 3D Printing can be classified as a competence-destroying technology (Tushman and Anderson, 1986), but only to a limited extent. The technicians' visual capability and knowledge about shells remained largely intact. As the new process was cleaner and enabled them to better do their job, they still had incentives to favor it. 3D Printing has also enabled hearing aid manufacturers to innovate along new dimensions related to fitting the electronics and using stored data to optimize hearing aid shells. Several firms, however, report that this potential has remained largely unrealized.

The technological challenges were particularly high for early adopters, primarily Siemens and Phonak, who started already in 1999 prior to the emergence of a dominant design. They were exposed to more uncertainty concerning which technology to use (SLS or SLA) and how to obtain suitable software and scanners. In some cases, this uncertainty resulted in problems as firms invested in the wrong technology and subsequently had to switch. These events stand in sharp contrast to firms adopting 3D Printing a couple of years later. By 2002–2003, biocompatible material was available for SLA and software and scanners from 3Shape had become accessible to anyone. As a consequence, late adopters such as Oticon and GN ReSound faced less technological uncertainty and could scale up the process with lower risk.

An important contribution of this article is therefore the classification of 3D Printing. In the hearing aid industry, the technology can be categorized as a *competence-destroying process innovation*. It was, however, sustaining rather than disruptive in the sense that the market demanded this technology and that there were clear financial reasons to pursue it. Competence-destruction only happened on the component level as the rest of the hearing aid product remained intact.

Having reviewed under what circumstance new technology results in competitive turbulence, the article has explained why 3D Printing did not result in any changes in market share. No entrants have joined the industry and shifts in market share between incumbents in recent years are attributed to other factors than 3D Printing. This finding is in line with what theory on technological discontinuities would suggest. 3D Printing only destroyed a fraction of incumbent competencies and since there were obvious financial incentives to make the change, incumbents could mobilize resources to do so, as predicted by Christensen (1997). Moreover, critical complementary assets such as market organizations, manufacturing and R&D related to signal processing were not affected. As printers, scanners and software have been available on the market almost from the onset of the technology, it has not provided firms with any significant source of differentiation.

Two important managerial implications emerged from this study. First, a transition to 3D Printing is associated with competence destruction, meaning that firms need to develop new skill sets. While it is important to do so at an early point, first movers face extensive technological uncertainty. Waiting until the dominant design and reduced uncertainty therefore seems to be an important success factor.

Having mapped and described how an industry adopted 3D Printing for manufacturing, it is still difficult to draw extensive conclusions from one case study. While this paper suggests that the introduction of 3D Printing will not result in extensive competitive turbulence, it is not possible to generalize from these findings. Further empirical investigations of how industries have transitioned to 3D Printing are therefore welcomed.

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