In 1931 Dr. B. Clark wrote in The Dental Digest: “Almost every writer in the field of dental esthetics and dental ceramics makes mention of the many difficulties encountered in the reproduction of tooth color...”. Yet, the research for this thesis started in 2007, 76 years after Clark’s words, and still this statement remains valid and still is the manner at which almost all scientific papers begin on this subject. The esthetic appearance of the natural tooth is comprised of many different factors making the tooth a specifically difficult object to determine its color. The subjective perception of color with the human eye is prone to a great many different types of illusions and variables. The fluctuating surrounding illumination and environment at which the human eye, the observer, perceives the color of the natural tooth does not make the process any easier. There are also many ways in which the artificial restorations, made out of dental materials, differ from the natural internal build-up of the human dentition. To end with, the final acceptance or rejection of these dental restorations are almost always based on the observer’s response. In short, this is the color problem in dentistry. These influences on tooth color perception, determination and reproduction
were considered within the scope of this thesis. This, in order to increase predictability and knowledge on tooth color science, recognizing the difficulty in single tooth color matching in the anterior region and the trends in esthetic dentistry where art is meeting science.

The general introduction in Chapter 1 provides background information on tooth color science, lays out the color problem in dentistry and describes the aims of this thesis. In color research, after measuring the reflectance of two objects, the calculated CIE $L^*a^*b^*$ values can be compared between measurements. $\Delta E^*$ is a measure of this color difference, providing a quantitative representation of the perceived color difference between a pair of colored objects under a given set of experimental conditions. $\Delta E^*$ has been used extensively in dental research, but there is a lack of agreement on what values of $\Delta E^*$ are considered to be the perceptibility and acceptability thresholds. That is why this thesis begins in Chapter 2 with a systematic review on perceptibility and acceptability thresholds in tooth color perception. The results of this research showed that a new prospective controlled (clinical) study is necessary to quantify a color difference threshold in order to be able to interpret all the aspects related to color research in dentistry and provide a consensus for dental researchers. It was concluded that at the moment most clinical studies refer to the same few papers that have attempted to determine perceptibility and acceptability thresholds from three decades ago under in vitro conditions. Such $\Delta E^*$ values are derived from the CIE $L^*a^*b^*$ color space which are measured electronically with tooth color measuring devices (CMD). There are many different CMDs available for dental clinicians and researchers and therefore before further research was further conducted, Chapter 3 looked at five different CMDs in order to study their overall performance in terms of repeatability and reliability. It was concluded that when compared to colorimeters and digital cameras, a spectrophotometer can be seen as the gold standard of color measuring devices in tooth color determination. Hereafter two different spectrophotometers were studied in Chapter 4 in order to evaluate whether the dental clinician can communicate with the dental technician if different spectrophotometers are being used. After the previous conclusion that spectrophotometers are the most repeatable instruments for determining color, the aim was now to see whether data can be exchanged between measurements taken with two different spectrophotometers. It was concluded that the exchange of $L^*a^*b^*$ values between two spectrophotometers cannot be recommended; yet the two devices match each other better when the output of the tooth color is given as the closest corresponding shade tab according to the device’s database.
Even though we have entered an era of digital dentistry, where CMDs have not only been extensively studied, but are also available to the dental clinician, still classical shade-guides are the method of choice in the daily practice. Seventy-six years ago the aforementioned article by Clark stated that the main problem was that a system of color measurement and color specification was lacking. The current commercial shade-guides are still inadequate. However, it would be impractical and commercially impossible to construct a shade-guide covering the entire field of natural tooth color and at the same time differentiating between the body and enamel colors. Furthermore it was acknowledged that a simple method for the measurement and specification of the colors found in teeth was necessary by means of an equipment. Now that we have systems for color measurement that are digital, it is also no longer impractical to construct a digital database with the range of the tooth color space, which is what was evaluated in Chapter 5. This chapter acknowledged the problem with contemporary shade-guides, which is that they inadequately cover the tooth color space. It was concluded that the newly developed color determination and color reproduction system, which was logically and systematically arranged and simplified could cover the range of human teeth below the level of perceptibility ($\Delta E^* \leq 1.6$) better than four other available contemporary systems. Before such a new concept can be adopted for general use though, successful clinical use has to be demonstrated in the future. Therefore, clinical research is necessary to show that the measured or visually assessed color match, using the newly developed system, can be precisely reproduced in porcelain restorations. After this study, I was able to see what Clark meant in 1931 with ‘a new and improved shade-guide system being commercially impossible’ as this may be still the very reason why even today the inadequate shade-guides are still being used. It is not only important to research a new shade-guide system, but to also research how to improve the use of the more traditional shade-guide systems already being used. This was investigated in Chapter 6. In this chapter the Vita Classical shade-guide system was arranged systematically according to Lightness ($L^*$) in order to test whether clinicians can score more often a correct shade match visually than with a conventional arrangement based on Hue groups. This was based on the theory that the human visual system contains more rods which are more sensitive to light and register brightness. The conclusion of this study was that dental clinicians who used the shade-guide system arranged according to an increase in Lightness were not more or less successful in selecting the correct tooth shade. Although, it was not evaluated within the scope of the study, the observation was made that when the shade tabs were arranged from light to dark, the process of color determination was quicker for the
clinician. The evaluation of ease and time would be variables to be tested in the future in a similar study.

Even before Clark, as early as 1924, Dr. Victor Sears wrote an article on “The Art side of Denture Construction”. This article recognized that translucency has an important effect on the eye. Color is known to have three dimensions, hue, value and chroma, but the fourth dimension should be recognized as translucency, especially with teeth as it plays a big role in color matching of restorations with the natural dentition, this is a conclusion also mentioned in Chapter 6. Further research on how to measure translucency was, and still is, indeed necessary to solve the color problem in dentistry.

Therefore in Chapter 7 two different concepts of the natural layering technique were evaluated in order to measure the effect of different thickness layers of composites on the overall translucency and color of a restoration. It was found that with the more modern concept of natural layering, which uses an ‘enamel’ composite and a ‘dentin’ composite of the same shade, but different translucency, more predictable results can be achieved with the final restoration. If a clinician uses a system based on the more modern concept, which always has the same highly translucent enamel layer over the dentin layer, it is more difficult to have control over the final outcome. A natural tooth is built up in different organic layers of different translucencies, and hence composite restorations give the best esthetic results when layered in the same manner. Not only did we look at the effect of layering of composites, but also at other dental materials such as porcelain and different colors of cement layers. Chapter 8 evaluated such color management when it comes to thin porcelain veneers. The conclusion of this study was that even when different shades of resin cements are used, the underlying tooth color cannot be masked.

Looking further into the behavior esthetic dental materials, the color stability of composite resins has been widely studied within dental research. However, composites are also available in natural gingiva colors and their color stability proves to behave differently as studied in Chapter 9. Significant change in color was seen between the different pink composites after what would be equivalent to eight months of exposure to the immersion media in the clinical setting. Looking at such color stability studies on dental materials, it brings light to the discussion on how valid the importance of the correct natural color of materials are, if they do not stand the test of time during function. To create the desired esthetic effect of a restoration is one thing, but it is another thing to be able to successfully maintain the esthetic results throughout a diversity of clinical circumstances and to demonstrate reasonable longevity.
As mentioned before, the evaluation of color differences are necessary within color research, and the CIE L*a*b* based color difference equation is generally and unanimously applied. In a recent PhD thesis of Dr. R.I. Ghinea 2013 (University of Granada, Department of Optics), it was reported that there is still an important gap between the perceived and computed color differences when using the CIE L*a*b* formula, and concluded that the CIE DE2000 color difference formula is better correlated with the visual perception, recommending its use in dental research and for \textit{in vivo} dental color measurements. The present PhD thesis has continuously used the CIE L*a*b* color space as this has been widely used in research and applications in the dental field, yet it is now recognized that future color research should indeed consider using the newer formula CIE 2000 as its better adequacy has now been proven.

“On the topic of color Dr. Victor Sears also wrote: “For the purpose of laying myself open to attack, let me tell you that my selection for the predominating Hue for full dentures is limited to practically five numbers”. He goes on to explain that the five colors are yellow or orange in their foundation, with exception of one which has a faint suggestion of pink. When I started the research for this thesis I would have been one to ‘attack’ such statements. I believed that the more colors there are available the more coverage there is of the tooth color space and that this in combination with a digital ‘recipe’ of the amount of pigmentation would be the answer to the color problem within dentistry. Yet towards the end of my research I am seeing that the above idea of Sears in 1924 is wiser than I originally thought. As I deepened my knowledge on color science within dentistry and especially on the phenomenon of the ‘blending-effect’ (also known as chameleon effect) I can see that the practical solution is to have no more than a few colors for the dental clinician; and that future research must be more towards this direction.”

Ghazal Khashayar