Face-space: A unifying concept in face recognition research.

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Running Head: Face-space: A unifying concept.

Word count: 13,656

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Abstract

The concept of a multi-dimensional psychological space, in which faces can be represented according to their perceived properties, is fundamental to the modern theorist in face processing. Yet the idea was not clearly expressed until 1991. The background that led to Valentine's (1991a) face-space is explained and its continuing influence on theories of face processing is discussed. Research that has explored the properties of the face-space and sought to understand caricature, including facial adaptation paradigms is reviewed. Face-space as a theoretical framework for understanding the effect of ethnicity and the development of face recognition is evaluated. Finally two applications of face-space in the forensic setting are discussed. From initially being presented as a model to explain distinctiveness, inversion and the effect of ethnicity, face-space has become a central pillar in many aspects of face processing. It is currently being developed to help us understand adaptation effects with faces. While being in principle a simple concept, face-space has shaped, and continues to shape, our understanding of face perception.

Keywords: face; recognition; caricature; adaptation; ethnicity.

Introduction

Development of formal models of human categorization and recognition requires a stimulus set in which the dimensions or features on which stimuli vary can be controlled. Artificial faces were a favorite stimulus set used to develop these models in the 1970s and early 80s (e.g. Goldman & Homa, 1977; Medin & Schaffer, 1978; Reed 1972; Solso & McCarthy, 1981). The stimulus sets were constructed in a similar manner to the ‘Identikit’ and ‘Photofit’ facial composite systems of the day (see Figure 1 for an example). A similar approach was also found in studies of cue saliency in face recognition (e.g. Davies, Ellis & Shepherd, 1977). The assumption, sometimes implicit, was that faces (or concepts) could be represented as a collection of interchangeable parts.

Figure 1 about here

During this period theoretical models of concept representation were becoming more sophisticated. Prototype models of concept representation (e.g. Palmer, 1975) were being challenged by exemplar models that postulated no extraction of a prototype or central tendency. Exemplar theorists demonstrated that empirical effects, previously interpreted as evidence of prototype extraction, could be explained by more flexible exemplar models (e.g. Nosofsky, 1986). But the concept representation literature was becoming increasingly remote from understanding how we recognize faces in everyday life. Understanding how stimuli like those shown in Figure 1 can be represented provided little insight into how the relevant features or dimensions are extracted from real images of faces to enable us to recognize and categorize real faces (Figure 2).

Figure 2 about here

Ellis (1975) published an influential review that highlighted the lack of theoretical development in the face processing literature. Responding to this criticism, a literature on the recognition of familiar (e.g. famous) faces developed, drawing on a theoretical framework from word recognition, especially Morton’s logogen model (e.g. Morton, 1979). This approach led to the development of a leadingmodel of familiar face processing (Bruce & Young, 1986). However, this model had little to say about the visual processing of faces or recognition of unfamiliar faces. The theory of recognition of familiar faces and of unfamiliar faces had become separated.

Face-space was motivated by the aim to find a level of explanation, relevant to both familiar and unfamiliar face processing, which avoided the theoretical cul-de-sac of cue saliency. The framework was intended to draw on theories of concept representation, while avoiding the lack of ecological validity of artificial categories of schematic face stimuli. An important principle was that face-space would capture how the natural variation of real faces affected face processing.

One of the theoretical contributions that Ellis (1975) reviewed was work on the effect of inversion on face recognition (Yin 1969). Goldstein and Chance (1980) had suggested that effects of inversion and ethnicity could both be explained by schema theory. They argued that as a face schema developed it became more “rigid”: tuned to upright faces and own-ethnicity faces. Support for the theory came from work showing that the effects of inversion and ethnicity were less pronounced in children who were assumed to have a less well developed, and therefore less rigid, face schema (Chance, Turner, & Goldstein, 1982; Goldstein, 1975; Goldstein & Chance, 1964; Hills, 2014). Schema theory provided an encompassing theory for face recognition but lacked the specificity required to derive many unambiguous empirical predictions.

Light, Kyra-Stuart and Hollander (1979) applied schema theory to study of the effect of the distinctiveness of faces. These authors demonstrated an effect of distinctiveness on recognition memory for unfamiliar faces. Recognition was more accurate for faces that had been rated as being more distinctive or unusual, than for faces rated as typical in appearance. Light *et al.* interpreted the effect of distinctiveness as evidence of the role of a prototype on face processing. Influenced by Goldstein and Chance’s application of schema theory and the work by Leah Light and her colleagues on distinctiveness in recognition memory for unfamiliar faces, Valentine and Bruce argued that if faces were encoded by reference to a facial prototype, an effect of distinctiveness should be observed in familiar face processing. Valentine and Bruce (1986a) found that famous faces rated as being distinctive in appearance were recognized faster than famous faces rated as being typical, when familiarity was controlled. Independent effects of distinctiveness and familiarity on the speed of recognizing personally familiar faces were observed (Valentine & Bruce, 1986b). The effect of distinctiveness was found to reverse with task demands. Distinctive faces were recognized faster than typical faces; but took longer than typical faces to be classified as faces when the contrast category was jumbled faces (Valentine & Bruce, 1986a). These effects of distinctiveness were explained in terms of faces being encoded by reference to facial prototype. The final chapter of Valentine (1986) aimed to provide an overarching framework to conceptualize the effects of distinctiveness, inversion and ethnicity, based upon the representation of faces by a facial prototype in multi-dimensional similarity space. Valentine (1991a) was the first publication of this framework. This paper added a version of face-space in terms of an exemplar model, without an abstracted representation of the central tendency. It also included empirical tests of predictions derived from the framework.

A Unifying Model

Face-space is a psychological similarity space. Each face is represented by a location in the space. Faces represented close-by are similar to each other; faces separated by a large distance are dissimilar. The dimensions of the space represent dimensions on which faces vary but they are not specified. They may be specific parameters, or global properties. For example, the height of the head, width of a face, distance between the eyes, age or masculinity may all be considered potential dimensions of face-space. The number of dimensions is not specified. Faces are assumed to be normally distributed in each dimension. Thus faces form a multivariate normal distribution in the space. The central tendency of the relevant population is defined as the origin for each dimension. Thus the density of faces (exemplar density) is greatest at the origin of the space. As the distance from the origin increases, the exemplar density of faces decreases. The faces near the origin are typical in appearance. They have values close to the central tendency on all dimensions. Distinctive faces are located further from the origin. The distribution of faces in face-space is illustrated in Figure 3.

Figure 3 about here

When a face is encoded into face-space there is an error associated with the encoding. When encoding conditions are difficult, the associated error will be high. Therefore, brief presentation of faces, presenting faces upside-down or in photographic negative will result in a relatively high error of encoding. Valentine (1991a) did not make any assumption that inversion required any specific theoretical interpretation. It has been argued that inversion selectively disrupts encoding of the configural properties of faces (e.g. Yin, 1969; Diamond & Carey, 1986). Face-space is agnostic on this issue; it merely treats any manipulation that reduces face recognition accuracy as increasing encoding error.

Encoding error is likely to result in greater difficulty in recognizing typical faces than in recognizing distinctive faces (Valentine, 1991a). Typical faces are more densely clustered in face-space than are distinctive faces, therefore an increase in the error of encoding is more likely to lead to confusion of facial identify for typical faces than for distinctive faces. There are fewer face identities encoded near distinctive faces. For a distinctive face, the target identity is more likely to be the nearest face in face-space even in the presence of a large encoding error. Valentine (1991a) predicted that presenting faces inverted at test would lead to a smaller impairment in the accuracy of recognition memory for distinctive faces than for typical faces. This prediction was confirmed for recognition memory of previously unfamiliar faces (Experiment 1 and 2). Inversion was also found to slow correct recognition and was more disruptive to accuracy of recognition of typical famous faces than of distinctive famous faces (Experiment 3).

An assumption of the face-space framework was that the dimensions of face-space were selected and scaled to optimize discrimination of the population of faces experienced. Development of face recognition was assumed to be a process of perceptual learning in which the dimensions of face-space were tuned to optimize face recognition of the relevant population. Valentine (1991a) applied face-space to understanding the effect of ethnicity on face processing. If it is assumed that an observer has encountered faces of only one ethnicity, with sufficient experience their face-space would be optimized to recognize faces of this ethnicity. If this observer now started to encounter faces of another ethnicity, faces from a different population would be encoded in the face-space (the other-ethnicity). Other-ethnicity faces would be normally distributed on each dimension of face-space but may have a different central tendency from own-ethnicity faces. Furthermore, some dimensions may not serve well to distinguish between other-ethnicity faces. But some dimensions that could serve well to distinguish the other-ethnicity faces may be inappropriately scaled to distinguish the faces optimally (i.e. the optimal weight required for dimensions may be different between populations). This situation is illustrated in Figure 4. The other-ethnicity faces form a relatively dense cluster separate from the central tendency of own-ethnicity faces. In this way face-space naturally predicts an own-ethnicity bias (OEB[1]) by which, dependent upon the observer's perceptual experience with faces, own-ethnicity faces are likely to better recognized than faces of a different ethnicity. Valentine and Endo (1992) found that distinctiveness affected accuracy of recognition memory for previously unfamiliar own-ethnicity and other-ethnicity faces. Distinctive faces were better recognized than typical faces in both own- and other-ethnicity populations. The effect of ethnicity on accuracy of face recognition (Valentine & Endo, 1992, Chiroro & Valentine, 1995) was attributed to the other-ethnicity faces being more densely clustered in face-space because the dimensions of face-space were sub-optimally scaled for other-ethnicity faces. With appropriate experience face-space becomes optimized so that own-ethnicity and other-ethnicity faces are recognized equally well. However, Chiroro and Valentine (1995) reported two qualifications to this effect. First, sheer exposure to other-ethnicity faces is not sufficient to learn to recognize the faces appropriately. It was only when the social environment required participants to learn to recognize a number of other-ethnicity faces that they showed the ability to do so. Second, participants who had learnt to recognize another ethnicity efficiently showed a small effect of recognizing their own-ethnicity less effectively than participants who had never encountered the other-ethnicity faces. This could have been predicted from the face-space framework, because the dimensions have been scaled to recognize two different populations requiring weights on dimensions that may be slightly sub-optimal for both populations. Recognizing faces from two populations efficiently is a more difficult statistical problem to solve than recognizing a single population.

Figure 4 about here.

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[1] It has been common practice in the literature to use the term "race". However the correct term is 'ethnicity', because there is only one human sub-species (race) alive on the planet (Homo Sapiens Sapiens). Even if 'race' is regarded as acceptable to refer to the major anthropological groups, it is incorrect (as is common in the literature) to use the term 'race' to refer to ethnicities such as 'Hispanic' who are, of course, Caucasian and therefore the same race as 'Whites'.

Care needs to be taken interpreting face-space when it is represented in just two dimensions as it is in Figures 3 and 4. Face-space was always envisaged as a multidimensional space with many more than two dimensions. Burton and Vokey (1998) describe the potential dangers of using a two dimensional representation of what should be a multi-dimensional space. They argue that, contrary to the intuition derived from a two-dimensional space, if a space with 1000 dimensions was populated with 1000 normally distributed exemplars, all of the exemplars would be a similar distance from the origin of the space; approximately 1000 times the standard deviation of the normal distribution. Hence, in a high-dimensional face-space there would be few highly typical faces close to the origin. This point was previously made by Craw (1995). As Burton and Vokey acknowledge it remains the case that, even in a very high dimensional face-space, the origin of the space is the point of maximum exemplar density and therefore the predictions of the effects of distinctiveness in recognition and classification tasks are valid.

A multi-dimensional space differs from the two dimensional illustration in the expected distribution of distinctiveness (typicality) ratings. The two dimensional figure leads to the expectation that many faces would be rated as highly typical with progressively fewer faces given higher ratings of distinctiveness. Burton and Vokey (1998) observed that, instead, typicality ratings of faces are normally distributed. Most faces are judged to have moderate levels of typicality, with few rated as highly typical, or highly distinctive. Burton and Vokey demonstrated that this distribution is predicted by a multidimensional normal distribution, as assumed in the face-space model. The point Burton and Vokey made was that it can be misleading to generalize from simple two dimensional representations to high dimensional spaces. Mathematic analysis, rather than intuition, is required to evaluate the predictions of such a model.

Although Burton and Vokey (1998) did not extend their analysis to consider the attractiveness of faces, their analysis does explain a paradox in the literature. Morphing faces to produce an average facial appearance produces a face that is strikingly attractive. This effect was first observed by A. L Austin (Galton, 1878, [see Valentine, Darling & Donnelly, 2004]) and more recently has been demonstrated formally (e.g. Langlois & Roggman, 1990; Perret, May and Yoshikawa, 1994). This work suggests that typical faces are highly attractive. The paradox is this: If typical faces are common in the population, why are highly attractive faces rare? Burton and Vokey's analysis provides the answer: very typical faces are rare; therefore highly attractive faces are rare. It is rare for faces that can vary on many dimensions to be average on all of them.

The original formulation of face-space did not specify the nature of its dimensions. It was always considered that the dimensions might be holistic (e.g. age, gender or face-shape). One way to operationalise face-space is to equate the dimensions of face-space with the components derived from principal component analysis of facial images or eigenfaces (Turk and Pentland, 1991). The concept of eigenfaces was developed by computer scientists as a method to compress the information in a set of faces. This conceptualization of face-space has been widely used by computer scientists and, amongst other applications, is used to generate synthetic composite faces. The approach is reviewed below under the section on forensic applications.

In summary, the face-space framework described by Valentine (1991a) unified the accounts of the effects of distinctiveness, inversion and ethnicity on face recognition. Valentine (1991b) extended the approach to include an account of caricature. The approach was to provide a framework which, although underspecified, could be applied to understanding variation in a real population of faces. Use of artificial stimulus sets was rejected as an appropriate tool to understand face recognition in the real world.

Norm-based coding vs. Exemplar model

Valentine (1991a) originally suggested two different models within the face space framework. The first was one in which faces are encoded relative to a specific prototypical face also known as a norm face. In this norm-based face-space, faces are coded relative to this central face. The stored representation can be seen akin to an angle in which the direction and the magnitude are required to define the location of a face within this space. The distinctiveness of a face is represented by the length of this vector whereas the direction defines the identity.

The alternative model of face-space offered in Valentine (1991a) was an exemplar-based version. In an exemplar-based face-space, the faces are represented in the space without specific reference to any central prototype. The distance between face representations provide the measure of their similarity and it is the distribution of faces within the space that leads to the distinctiveness effects described above. Distinctive exemplars will be in areas of low density of other exemplars as a consequence of the normally distributed pattern of faces that one sees and knows. Typical faces, on the other hand, will be located near the centre of the distribution and thus there will be many similar face representations with which to confuse a particular exemplar.

This distinction between norm-based and exemplar-based versions of face-space reflected wider debate on the nature of memory. Exemplar-based models of memory were developed (e.g., Medin & Schaffer, 1978; Nosofsky, 1986;1988; 1991) as an alternative account of memory to category knowledge based on the extraction of prototypes (e.g., Goldstein & Chance, 1980; Knowlton & Squire, 1993; Palmer, 1975; Reed 1972). There has been a great deal of research that has been conducted on the domain of face perception that speaks to the differences between these two models of face-space, included research on the own-ethnicity bias, caricature recognition and more recently facial adaptation effects. The contribution of each of these topics to our better understanding of face-space will be reviewed in turn, but first it is worth looking at the formulations of these two differing models in more detail.

Similarity metrics

To formalize the differences between norm-based face-space and exemplar-based face-space it is necessary to consider the similarity metrics that define them. A basic assumption for all metrics is that faces that are similar are encoded close together in the space, and therefore are confusable. While all versions of face-space suggest that faces are encoded in a multi-dimensional space, the properties of this space can differ. The most important property is how similarity of two faces maps onto distance in the face-space. This is the similarity metric.

As a working hypothesis, Valentine (1991a) defines the similarity metric for the exemplar-based model as the simple Euclidean distance between the exemplars. Recognition takes place if a target's representation is sufficiently similar to an encoded representation of a known exemplar but sufficiently dissimilar from the next most similar encoded exemplar. A development of this recognition decision based on an exemplar-based similarity metric was employed in the computational implementation by Lewis (2004) called face-space-R. In this model, a distribution of 'faces' was generated such that they were normally distributed on each dimension of face-space (i.e. a multi-dimensional normal distribution) and tested in a variety of tasks. The similarity metric employed was such that two identical faces had maximal similarity but similarity between faces decreased as Gaussian decay function with distance in the space. Lewis demonstrated that findings concerning distinctiveness, ethnicity and caricatures could be accounted for using this similarity metric.

One consequence of this type of exemplar-based similarity metric is that if two faces differ by the same distance in the space they will be equally similar regardless of whether they are typical or distinctive. There is now some evidence that this is not the case. Ross, Hancock and Lewis (2010) generated sets of stimuli where the same physical change was either applied such that the modified face lay on a radial line from the average face to the location of the original face in face-space, or the new location was oblique to a line between the exemplar and the average face. A discrimination task found that changes along the radial line from average (norm) face were harder to detect than changes that were oblique to that line.

The similarity metric for the norm-based model was not clearly defined in Valentine (1991a) except for the suggestion that it was based on vector similarity. Some authors have taken this to mean the dot product of the vectors. However, the dot product would predict that two vectors, representing different faces, would appear more similar to each other as one of them increased in magnitude (e.g. became more distinctive by being caricatured). Byatt and Rhodes (1998) proposed a similarity metric defined by the cosine of the angle between the vectors' representations of two faces (relative to a norm face) divided by the simple distance between the two faces. The benefit of this metric was that faces that were on the same radial axis were more similar to each other than those that where equidistant but were not on the same radial axis. The metric was also able to distinguish between two faces that lay on the same radial axis but were still different distances from the average face.

The question as to the correct metric for face-space cuts right to the definition of face-space itself. If the metric is not calculated relative to a norm face then the face-space is not norm-based. There remains no consensus on the correct interpretation of the similarity metric. As such, the question as to the role of a norm face in face recognition remains an open one.

Caricatures

The recognition of caricatures has been influential, but controversial, in revealing the nature of face-space. Artists' portrayals of caricatures are better recognized than veridical images (Perkins, 1975). A similar finding was found with computer-generated caricatures (Benson & Perrett, 1991). Such computer-generated caricatures can be produced by the following process. The location of many facial landmarks, which define the shape of the face's appearance (e.g. corners of eyes, outline of the nose etc.), are recorded for many faces from a homogeneous population (e.g. male White faces). The locations are averaged to define a 'norm' or 'prototype' face. A computer-generated caricature of an individual face can then be generated by exaggerating all the differences in the location of the landmarks between the individual face and the average face by a fixed proportion (e.g. 30%, 50%, see Figure 5). The proportion of the exaggeration defines the extent of the caricature. The visual texture can then be scaled and re-mapped to fit the new facial shape. This process exaggerated distinctive features. For example, an atypically large nose becomes even larger in a computer-generated caricature. Anti-caricatures (in which differences from the average were reduced) were also constructed.

Figure 5 about here

The fact that caricatures are recognized more accurately than veridical images is most easily explained by norm-based versions of the face-space. A caricature will have a representation that has the same angle from the prototypical face but will have a longer vector. This longer vector has been argued to be the parameter that provides the improved recognition of caricatures over veridical faces; in effect the caricature is a super-stimulus of the facial identity.

The exemplar-based version of the face-space, however, is not silent on the topic of caricatures. This is because, although exaggerating a face away from the average makes the face more unlike its target representation, it also makes it less like any competitor representations as well. Lewis and Johnston (1999) had shown that an advantage for recognition was found for images that were exaggerated away from other similar known faces. This fact was used in the face-space-R model (Lewis, 2004) to demonstrate how an exemplar-based face-space predicts better recognition for a caricature face over a veridical face. The model was also able to make estimates of the degree of caricature that would lead to optimal recognition. Through modelling the caricature data, Lewis was able to make an estimate for the number of dimensions that we may use in a face-space. The estimate was between 15 and 22 dimensions.

The fact that both the norm-based model and the exemplar-based model can predict a recognition advantage for caricatures has recently become an interesting issue, as the existence of a caricature advantage has been drawn into question. The studies that do show a strong caricature advantage tend to use impoverished stimuli either because they are line drawings (e.g., Rhodes, Brennan & Carey, 1987) or because they are presented briefly (Lee & Perrett, 1997). Some studies only show an advantage for caricatures over anti-caricatures (Lewis & Johnson, 1998). More recent studies demonstrate no advantage for the caricature (Kaufmann & Schweinberger, 2008) or even an advantage for the anti-caricature (Allen, Brady & Tredoux, 2009). Indeed, Hancock and Little (2011) suggest that the reason for the caricature advantage observed in earlier studies was at least partly due to adaptation effects as a result of the way in which the stimuli were presented. Exactly how these adaptation effects work and what they tell us about face-space is explored further below. The situation is that there are two models that each predict a caricature advantage but there is debate over whether the effect on recognition is real or an artifact. Further research is required to resolve this.

Facial adaptation.

Facial adaptation effects have demonstrated how the face-space is a flexible concept and representations can be distorted within it. Adaptation is a recalibrating process in which the perceptual system is altered following constant stimulation of a particular stimulus characteristic (Blakemore, Nachmias, & Sutton, 1970). One of the first demonstrations of face adaptation was shown by Lewis and Ellis (2000), although they used the term satiation rather than adaptation. They showed that the time required to recognize a face increased when 30 different views of that face had been presented immediately before the test (compared with just 3 different views). As well as slowing recognition, adaptation also causes contrastive after-effects, such that adaptation to a center-compressed facial image causes the perception of an unaltered image to appear center-expanded (Rhodes & Jeffery, 2006; Webster & MacLin, 1999; see Figure 6). This is the typical face distortion after-effect (FDAE). Contrastive facial after-effects have also been observed for judgments of attractiveness (Rhodes, Jeffery, Watson, Clifford, & Nakayama, 2003), personality (Buckingham et al., 2006; Wincenciak, Dzhelyova, Perrett, & Barraclough, 2013), emotion and gender (Webster, Kaping, Mizokami, & Duhamel, 2004) and identity (Leopold, O'Toole, Vetter, & Blanz, 2001; Leopold, Rhodes, Müller, & Jeffery, 2005).

Figure 6 about here.

Face after-effects transfer across face identities (even to the perceivers' own face; Webster & MacLin, 1999), from an adaptor of one size to test stimuli of a different size (Zhao & Chubb, 2001), across different parts of the retina (Hurlbert, 2001; Anderson & Wilson, 2005) and partially across viewpoints (Jeffery, Rhodes, & Bussey, 2006; Pourtois, Schwartz, Seghier, Lazeyras, & Vuilleumier, 2005; Ryu & Chaudhuri, 2006), yet visual similarity between the adaptor and test is a critical variable in the magnitude of the FDAEs (Yamashita, Hardy, De Valois, & Webster, 2005) at least for unfamiliar faces (Hills & Lewis, 2012). For familiar faces, there is greater transference across size and viewpoint (Carbon & Leder, 2005; Jiang, Blanz, & O'Toole, 2006), indicating that face after-effects involve higher-level perceptual processing than observed in other after-effects.

Not all kinds of distortions can cause the FDAE, however. Robbins, McKone, and Edwards (2007) demonstrated that after-effects were observed when participants were adapted to a “natural” facial configuration (eyes aligned) but not when adapted to “unnatural” facial configurations (eyes not aligned). The after-effect transferred from the adaptor identity to other faces. This indicates that adaptation techniques may be useful in revealing the nature of the dimensions of face-space.

Often considered similar to FDAEs are face identity after-effects (FIAEs; Strobach & Carbon, 2013; Webster & MacLeod, 2011), whereby the perceived identity of a face is altered after adaptation to a particular identity. Leopold *et al*. (2001) morphed together 200 faces to produce a prototype face. This was assumed to be the centre of the face-space. Each unique face identity could be measured in terms of Euclidean distances from the prototype face. After adaptation to an anti-face (a projection through the origin of face-space in the opposite direction from the face-identity), the identification threshold (the required identity strength to perceive the face identity) was lowered by 12.5% suggesting it was easier to perceive the identity following adaptation (see Figure 7). These effects are considerably weaker if the adapt and test face continuum do not pass near the norm (Zhao, Hancock, & Bednar, 2008). Nevertheless, since they are still present, these results demonstrate that adaptation to one particular face alters the entire face-space (Benton & Burgess, 2008).

Figure 7 about here.

These facial adaptation effects are easily explained in terms of the face-space using Clifford, Wenderoth, and Spehar's (2000) notion that the sensory system dynamically maps environmental attributes onto patterns of fixed neuronal responses. This mapping is changed when the structure of the environment is altered. Implicit within this model is that neuronal populations have tuning curves for particular stimuli characteristics which may correspond to dimensions of face-space. The width of tuning curves represents the population’s response bandwidths, whereas the peak represents the preferred stimulus property. The perceived response is given by the weighted vector average of the units responding to the stimulus, based on distribution-shift theory (c.f. Mather, 1980). The purpose of adaptation is to recentre the perceptual space nearer to the adaptor stimulus (Hurlbert, 2001; Webster & Macleod, 2011). Evidence for the renormalization process of adaptation stems from the fact that it is not possible to adapt to a prototype face (Webster & MacLin, 1999). This renormalization process leads to apparently permanent changes in the face-space (Carbon & Diyte, 2012) suggesting a role for adaptation is face learning and the creation of the face prototype in face-space. For example, consistently seeing faces with a wide nose alters the face prototype, such that wide noses are considered typical and narrow noses distinctive.

Researchers have also used adaptation to conceptualize the neural representation of the dimensions of face-space. Typically, two-pool models have been employed to account for what appears to be opponent processing (e.g. Over, 1971) and have been successfully implemented in modeling the FIAE (Ross, Deroche, & Pameri, 2014). At one end of each dimension there is a neural population for the extreme of a particular feature and at the other end of that same dimension, there is a neural population for the opposite extreme of the same feature (e.g. Robbins et al., 2007, see Figure 8). Equal activation of both pools of neurons signals a neutral point on that dimension (i.e. the norm). The relative firing of each pool determines the size of the feature seen. Coding is therefore relative to norm. Based on this model, after-effects increase monotonically with increasing adaptor extremity (at least up to an ecologically valid range of values). This is due to more extreme adaptors activating their preferred channel more strongly (Pond, Kloth, McKone, Jeffery, Irons, & Rhodes, 2013). Consistently, many face after-effects are found to be larger for strong (e.g., extremely large or unusual) than weak adaptors indicating norm-based coding for many facial attributes (Burton, Jeffery, Skinner, Benton, & Rhodes, 2013). Concurrently, evidence from fMRI adaptation and single-cell recording studies indicate that face-selective neurons are tuned to encode the distinctiveness of individual faces relative to the prototype face (Leopold, Bondar, & Giese, 2006; Loffler, Yourganov, Wilkinson, & Wilson, 2005).

Figure 8 about here

While this two-pool account is appealing, there are caveats with it. There is evidence to suggest that some of the dimensions along which faces are thought to vary are not orthogonal: the effects of adaptation on one dimension may depend on the levels of other dimensions (Jaquet & Rhodes, 2008). Studies have shown that when participants are adapted to opposing pairings of facial characteristics category-contingent after-effects are typically produced (e.g. adaptation to expanded eye spacing in White faces and constricted eye spacing in Black faces at the same time causes contrasting after-effects in White and Black faces). Aftereffects are not therefore based on the simple translation of experienced face-space relative to physical face-space. Therefore, norms for different face categories can be established depending on the context. Thus, there may be separate face-spaces for different categories of faces (Little, DeBruine, Jones, & Waitt, 2008). Furthermore, FIAEs caused by familiar faces are only observed if the familiar face is recognized (Laurence & Hole, 2012), suggesting the involvement of higher-level recognition-based systems at play in the face-space.

Adaptation effects can also be explained within a multichannel or exemplar-based version of face-space where a facial attribute is represented by activation in many pools of neurons. Each pool is tuned to a narrow range of distinct values. An exemplar of a feature is represented by the summation of activation in several of these pools. These pools are maximally tuned to naturally occurring values. Therefore, extreme adaptors (outside the range that would be expected in the real-world) would cause less after-effect than less extreme adaptors as they have less impact on the channels in the less extreme range. These results have recently been modeled (Ross et al., 2014) indicating that an exemplar-based model of face-space can account for after-effects.

Adaptation can also speak to how inverted faces may be represented in the face-space. In Valentine's (1991a) original model, inversion leads to increased error in encoding. Research exploring after-effects and orientation show that after-effects occur for upright and inverted faces, but only if the orientation of the adaptation face was matched with the orientation of the test faces (Webster & MacLin, 1999). This suggests that inverted faces are not processed in the same face-space as upright faces, or that the dimensions used to code faces are orientation specific. Such category-contingent after-effects further indicate the possibility of their being many face-spaces. This begs the question of how many face-spaces there are and how they may be structured: It is possible that there is a hierarchical structure whereby there is a face-space for faces overall with further spaces for specific categories (such as male/female), or that multiple spaces exist and motivation dictates which space is used. These are clear avenues for further research. Whether face after-effects are best accounted for in a norm-based or exemplar-based face-space, there is no doubt that the original model of face-space has proven to be a useful framework with which to explore after-effects. Importantly, these high-level face-specific after-effects and presumably neural response in face-space, correlate with face recognition accuracy suggesting the more responsive an individuals' face-space the better they are at face recognition (Dennett, McKone, Edwards, & Susilo, 2011).

Own-ethnicity bias

Valentine's (1991a) explanation of the OEB is based on the observed fact that other-ethnicity faces do not vary consistently along the same dimensions as own-ethnicity faces, due to the physiognomic differences (for example between Black and White faces, Ellis, Deregowski, & Shepherd, 1975). Indeed, Papesh and Goldinger (2010) have shown, using a multidimensional scaling (MDS) approach, that participants' perceptual space grouped highly controlled Black and White faces separately, with other-ethnicity faces grouped more densely in the MDS space. This grouping was based on structural properties of the faces rather than skin tone. These results are entirely consistent with face-space and indicate that the dimensions used for encoding and recognition of own-ethnicity faces are diagnostic and appropriate, but are unlikely to be as diagnostic for the processing of other-ethnicity faces (Hills & Lewis, 2011). Based on this idea, a number of authors have attempted to reduce the OEB by training participants to focus on features that differentiate other-ethnicity faces (Slone, Brigham, & Meissner, 2000). Hills and Lewis (2006) trained White participants to use the features typically described by Black participants when recognizing faces. This led to a reduction in the OEB amongst White participants because they looked at the diagnostic features (Hills & Pake, 2013).

While this explanation of the OEB is parsimonious, there are other recognition biases that are harder to explain within the face-space framework. The own-age (Anastasi & Rhodes, 2005, 2006), own-gender (Wright & Sladden, 2003), and own-university biases (Bernstein, Young, & Hugenberg, 2007) are not based on extensive experience: participants are likely to have roughly equivalent experience of own and other-gender faces; participants are less able to recognize faces younger than their own age, even though they were once young (Hills,2012). And finally, own-university biases are not based on physical differences between groups of faces. These biases may be explained in terms of motivation to process own-group faces deeply (Sporer, 2001). Nevertheless, expertise is required to differentiate and process faces deeply.

To explain these biases within the face-space framework, one can assume that dimensions that are diagnostic for differentiating between other-age faces can become more heavily–weighted and therefore more salient, depending on the age of the participant. Indeed, recent daily-life contact influences the magnitude of the own-age bias (e.g., Wiese, Komes, & Schweinberger, 2012). This perspective indicates that the face space adapts to the present living conditions. A useful analogy is to think of face-space around own-age and own-gender faces being stretched, to make these faces more dissimilar to each other and therefore easier to distinguish (cf. Nosofsky, 1986), akin to perceptual warping (Kuhl, Williams, Lacerda, Stevens, & Lindblom, 1992). This inherently adds a flexibility element to face-space. Dimensions do not have to be used equivalently in every situation, but can be weighted according to the task and motivation. A lack of motivation to process other-group faces may also lead to some dimensions being weighted more than others, leading to increased error during the encoding. This indicates an unanswered question regarding how own- and other-age faces are distributed within the face-space and how this changes with age.

Development of face–space

Given the importance of face-space for explaining how adults encode faces, it is important to apply this model to the development of face recognition. Face recognition abilities improve through childhood (e.g. Blaney & Winograd, 1978; Ellis & Flin, 1990; List, 1986). This improvement may follow a linear pattern (Feinman & Entwisle, 1976; Hills, 2014) and is associated with better memory for faces in children (Dempster, 1981; Hills 2012) and faster responding (Johnston & Ellis, 1995). Children's face recognition is inexpert. Children show a smaller effect of inversion on face recognition than do adults, when tested using appropriate methods (de Heering, Rossion, & Maurer, 2012; Hills, 2014; Rose, Jankowski, & Feldman, 2002). Children recognize typical and distinctive faces equally well (Johnston & Ellis, 1995). Some effects are simply observed differently. Children can be adapted to unnatural facial configurations that adults cannot (Hills, Holland, & Lewis, 2010).

These effects can be interpreted within the face-space framework. Evidence suggests that the face-space or prototype face becomes increasingly more refined with age enabling improved differentiation of categories of faces to be made (Short, Hatry, & Mondloch, 2011). This refinement may stem from children's use of the dimensions of face-space, the distribution of faces within face-space, or the use of the prototype. These three possibilities relate to the number of dimensions of face-space, the coding accuracy along the dimensions, and the coding of the prototype.

Johnston and Ellis (1995) presented the uniform model of face-space, in which the number of dimensions of face-space is constant throughout development. The distribution of faces within face-space changes, starting with an empty face-space. As faces are encountered, they are stored in the space. This creates crowding in the centre of the face-space and leads to typicality effects and own-group biases that will not be present in younger children.

An alternative position is that children may use fewer dimensions than adults (Nishimura, Maurer, & Gao, 2009). These may be "less appropriate" dimensions than those of adults (Johnston & Ellis, 1995 pp. 463), suggesting that dimensions will be added to the face-space during development (Lewis, 2004; Valentine, 1991a) when two faces cannot be readily discriminated with the existing dimensions. Perceptual learning (e.g. McLaren, 1997; Mundy, Honey, & Dwyer, 2007) indicates that when two similar stimuli are presented, participants will attend to the unique differences between the stimuli and inhibit the similarities. Therefore, a dimension that distinguishes between the two faces may be added to the face-space. This process will continue until most faces are recognizable. Thus, experience of faces dictates what dimensions will be added to face-space. With this position, there is no specificity about when dimensions will no longer be added to the space.

A third position is that children may use different or a larger number of dimensions than adults (Hills *et al*., 2010). Perceptual narrowing effects (Nelson, 2001; Macchi-Cassia, Kuefner, Westerlund, & Nelson, 2006), by which younger infants are better able to discriminate between pairs of monkey faces and phonemes of non-native languages than older infants (Cheour, et al., 1998; Kuhl, et al., 1992; Lewkowicz & Ghazanfar, 2006; Pascalis, de Haan, & Nelson, 2002; Scott, Shannon, & Nelson, 2005, 2006), indicate that with development children learn to orient their perceptual attention to the most relevant characteristics (Saarinen & Levi, 1995). Similar perceptual narrowing has been shown to occur in other realms of expertise such as chess (e.g. Gobet & Simon, 1996a, b) and is based upon the ability to form category boundaries. Category boundaries are associated with face expertise (Angeli, Davidoff & Valentine, 2008; Balas, 2012). Therefore, it is possible that experience narrows the number of dimensions used to recognize faces ensuring that only the most appropriate dimensions remain for frequently encountered faces. Potentially, children may rely more on featural dimensions, as opposed to configural dimensions, than adults and this may explain smaller face-inversion effects. With age, the face-space becomes more refined and specific to the most frequently encountered faces (upright, own-ethnicity faces) and this is evidenced by apparent coding changes with age. There is neurological evidence for such a possibility: the number of axons in the visual cortex decreases with age leading to more restrictions in the stimuli that lead to neural responses due to neuronal pruning (Johnson & Vecera, 1996).

A final position is that children may not be able to code faces precisely along the same dimensions as adults (Mondloch & Thomson, 2008). Potentially, the neural response is less distinct for a particular feature. This may lead to a less stable face norm (Nishimura *et al.,* 2008). The less stable norm may reflect the change from concrete to formal operational thought in Piagetian terms (Piaget, 1952). Whereas concrete operational thought involves simple flexible schemas, formal operational thought involves the use of many more complex schemas (c.f. K. Nelson, 1981; 1996). Therefore formal operational thought could lead to the development of a robust, ‘rigid’ prototype derived from the most frequently encountered faces.

All of these versions of face-space make similar predictions regarding the face processing abilities of children: Children show reduced ability to recognize faces, smaller face inversion, distinctiveness, and own-group bias effects. Distinguishing between these models will prove a challenge for future research. The number and use of dimensions of face-space in childhood remains an open question for future research. A further question relates to how the face-space develops in older adulthood. There is evidence to suggest that the face-space remains sensitive to the faces encountered in daily-life even into older adulthood (Wiese et al., 2012) despite changes in overall memory performance (Komes, Schweinberger, & Wiese, 2014). This leads to another line of further enquiry based on face-space: how does it change in latter adulthood when perception and memory abilities change?

Forensic applications of face-space.

We conclude this review by considering two practical applications of face-space in eyewitness identification. The first application directly uses an image-derived face-space to represent, and manipulate facial appearance. The second application is the design of an effective but fair technique to test a witness' ability to identify a suspect with a distinctive feature. To evaluate lineups, memory for facial appearance and separately for an additional distinctive feature is modeled using a hybrid model in which faces are represented both by their location in a multi-dimensional face-space and in terms of shared and unshared discrete features.

Computer-generated facial composites.

If an eyewitness is available to an investigation of a serious crime, but there are few other lines of enquiry, the police may ask the witness for help constructing a likeness of the offender. Construction of a likeness– known as a facial composite- would normally only be attempted with a witness who had a good opportunity to view the offender's face. The composite can be circulated to police officers or the media, in the hope that somebody who knows the offender will provide a possible identification and so open a new line of enquiry. In the past facial composites were constructed, under the guidance of the witness, using systems that physically swapped facial features (e.g. eyes, nose, mouth) until an acceptable likeness was achieved (e.g. Photofit, Identikit). These systems performed poorly and the composites produced were seldom recognized. The requirement to compare and select face parts out of the context of a whole faces is a difficult task. Human face recognition is strongly influenced by the subtle configural relationships between facial features. See Davies and Valentine (2007) for a review and evaluation of facial composite systems

A new generation of composite systems have been developed which draw on the representation of faces within face-space to 'evolve' a facial appearance, using a genetic algorithm to search face-space under the guidance of the witness for a suitable likeness. The major difference is that the new systems only ever require a witness to compare whole facial images. In this way the new 'holistic' systems exploit more effectively the natural style of human face processing.

A facial image similarity space, similar to the concept of face-space, can be constructed for a large set of standardized facial images by using a statistical method – Principal Component Analyisis (PCA) - to extract a set of orthogonal factors which serve as the dimensions of the space. These principal components, or 'eigenfaces', are extracted in the order in which they capture the variance in set of images (e.g. Turk & Pentland, 1991). Eigenfaces can be thought of as representing the dimensions of face-space. Once the eigenfaces are specified, any facial appearance can be represented by a set of weights for each component. The facial appearance can be reconstructed by combining the eigenfaces in the appropriate proportions specified by the weights. Any (artificial) facial appearance, can be constructed by a novel combination of weights, within the constraints of the variation of the original population of faces used to construct the space.

Eigenfaces capture variance across the entire image. Therefore they are holistic in nature and do not break faces down into component parts. Visualizing a principal component may be interpretable, for example, as representing gender (e.g. O'Toole, Abdi, Deffenbacher & Valentin, 1995) but most components are not interpretable. The face-space generated by principal component analysis of facial images displays an important property: faces represented close in the space are perceived as similar (Tredoux, 2002). Holistic systems for facial composite construction are now in common use by police forces. EFIT V and Evo-FIT are the most widely used systems in the UK. EFIT V is also used in the USA, Canada, Caribbean, and South America. See Frowd (in press) for a recent review of psychological research on holistic facial composite systems.

The construction of a facial composite by a witness begins by the generation of a random set of (artificial) facial images within the PCA space. The witness then selects the image or images that are most similar to the appearance of the culprit. In the initial set there will be a wide range of facial appearances and none are likely to closely resemble the culprit. The selection made by the witness is then used to 'breed' a new set of images introducing mutations around the 'parent' face or faces. The process is repeated iteratively, with each successive 'generation' becoming more similar to the culprit and to each other. The process continues until the witness cannot choose because all of the faces resemble the culprit equally well, or it becomes clear that the search of face-space has failed to converge on the desired appearance.

Sometimes a witness says that the offender looked more masculine, or younger than the current composite image. This kind of manipulation would be impossible in the earlier feature-based systems, but can be easily implemented in a holistic system by identifying the direction in face-space that relates to the perception of these characteristics. Solomon, Gibson and Maylin (2012) described a procedure to identify the relevant dimensions using EFIT V.

Participants are asked to classify a set of faces into binary categories (e.g. male or female), or rank order faces on a relevant dimension (e.g. age). In the latter case, a median split was then used to create two categories. A prototype for each category is then derived from the category members. The direction of the required manipulation in face-space (e.g. to increase masculinity) is given by the difference vector from the female prototype to the male prototype. A slider can be provided in the software interface, which applies a manipulation along this dimension. The perceptual effect is to apply a global transformation that make faces look more masculine or feminine depending on the direction of travel. This approach can be applied to any characteristic on which faces can be ordered or categorized.

In summary, conceptualizing the population of faces as represented in a similarity space (face-space), and implementing that concept as an image-space for a carefully standardized set of images, has allowed computer scientists to make a radical change in the construction of facial likenesses by witnesses. Commercial software has given the police a powerful new tool to identify offenders.

Designing lineups to identify suspects with distinguishing features.

If a witness sees a perpetrator with a distinguishing facial mark or feature (e.g., a scar, tattoo or piercing) it is very likely that the witness will describe the feature in the description they give to the police; and quite possible the witness can recall little else about the perpetrator’s facial appearance. Subsequently, a suspect may be arrested principally because they have a distinctive feature that fits the witness’ description. If the suspect disputes identification, the police in England and Wales are required to construct a lineup to test the ability of a witness to identify the suspect. The question arises of how a fair lineup can be constructed for a suspect with a distinguishing facial feature. If only the suspect has a tattoo or piercing, it will be clear to the witness which lineup member is the suspect and the procedure would be unfair to an innocent suspect.

Currently the police have two options: to conceal the distinguishing feature, or to replicate the feature on all lineup members. In England and Wales the police almost always conceal the mark, because concealment can be automated and applied to moving images used in the standard video identification procedures. Replication has to be applied by hand and can only be applied to still images. The disadvantage of concealing a distinguishing feature is that it changes the appearance of the suspect’s face. A distinctive feature is a salient cue to recognizing the face of a perpetrator (Winograd, 1981). By the encoding specificity principle, if the suspect is guilty, recognition memory performance will be determined by the overlap of cues present at encoding and test (Tulving & Thomson, 1973). Therefore, a better strategy is to replicate the feature on the foils in the lineup, leaving the appearance of the suspect unchanged. If replication is used, current procedure is to replicate the identical feature on the faces of all foils.

The hybrid-similarity model of recognition memory (Nosofsky & Zaki, 2003) was applied by Zarkadi, Wade, and Stewart (2009) to model eyewitness performance for ‘concealment’ and ‘replication’ lineups. In the hybrid-similarity model, similarity between two faces is a combination of the distance between the faces in a multidimensional similarity space or face-space (Nosofsky, 1986), and the number of discrete features that are shared and unshared (Tversky, 1977). The simulation predicted that replication would yield more culprit identifications from culprit-present (CP) lineups without increasing mistaken identifications of a foil from culprit-absent (CA) lineups. (A culprit-absent lineup in shown to a witness when the suspect is innocent – the real culprit is not in the lineup.) The predictions derived from the hybrid-similarity model were confirmed experimentally by Zarkadi *et al.* (2009). Perpetrators with a distinguishing mark (a bruise, a mole, a piercing, a moustache, a scar, or a tattoo) were more likely to be identified from a six-person simultaneous photograph lineup when the mark was replicated on all lineup members, then when the distinguishing feature was removed from the culprit (concealment). Whether the distinguishing feature was replicated or concealed did not affect the number of foil identifications made from a culprit-absent lineup.

Following police practice, Zarkadi *et al.* (2009) applied replication by exactly replicating the culprit’s distinguishing feature on all foils. This strategy means that the witness cannot use their knowledge of the distinguishing feature to recognize the perpetrator, if present in the lineup. Theory of memory suggests that both concealment and replication strategies are sub-optimal. Valentine, Hughes and Munro (2009) argued that including some variation in the replication of the distinguishing feature on the faces of foils would increase the probability of identifying a guilty suspect without increasing the risk of mistaken identification for an innocent suspect. The distinguishing feature should be replicated with variation within the constraints of the description of the feature given by the witness. For example, if the witness stated that the culprit ‘had a scar on his right cheek’; the length, orientation and location on the cheek could differ among lineup members. The rationale is that if the culprit is present, witnesses can use their memory of the distinguishing feature to identify him. Variation will not bias the lineup against an innocent suspect who the witness has not seen before. Research on this technique is still in progress. Preliminary data showed that 40% of witnesses identified a culprit with a scar from a ‘replication with variation’ lineup compared to 25% from an exact ‘replication’ lineup (Valentine and Zarkadi, 2012). There was no difference in misidentification rates from culprit-absent lineups.

Summary

Face-space, as described in Valentine's (1991a) paper, has inspired many researchers throughout the world, having been cited more than 600 times (Web of Science). The implementation of this model has inspired work evaluating theories of caricature and adaptation effects in face recognition, explaining similarity effects, and the own-ethnicity bias. In this review, we have described how the face-space has contributed to these areas of research and also presented new avenues for further research, in which face-space may provide a unifying explanation for more effects in face recognition. There are clearly many research questions worth investigating that concern the development of face-space, the neural representation of face-space, and the application of face-space in forensic and applied settings. The debate between proponents of exemplar- and prototype-based versions of the face-space, has been given a new lease of life in the context of facial adaptation and continues to attract research attention. We hope face-space will continue to inspire new researchers to explore the fascinating questions of how we process and recognize faces.

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