Mullite and the mystery of Hessian wares

Crucibles popular in the Middle Ages owed their success to an ingredient used in modern ceramics.

Crucibles from the German region of Hesse have been used since the late Middle Ages by alchemists, chemists, assayers, minters and metallurgists, but the factors responsible for their superior quality are unknown and several historically documented attempts to replicate their construction have failed. Here we show that the secret behind the remarkable properties of these early crucibles is mullite, an aluminium silicate that is now widely used in modern advanced ceramics.

Hessian crucibles (Fig. 1a) were established by the fifteenth century and dominated the international market, reaching Scandinavia, Britain, Portugal and even Jamestown in the American colony of Virginia. We analysed 50 Hessian and non-Hessian crucibles from 10 archaeological sites in Europe and America in an attempt to explain the superior properties of the Hessian vessels, or, as Robert Plot put it in 1677, “the mystery of the Hessian wares”.

Petrographic and chemical analyses revealed that the Hessian vessels were made to a standardized recipe, in which a very lean kaolinitic clay was used, tempered with almost pure quartz sand, then shaped on a potter’s wheel and fired to very high temperatures. The ceramic matrices of these crucibles have an exceptionally high alumina content (mean, 36.9 wt% ± 0.39 s.d.), with the sum of the alkali and earth-alkali oxides being just about 2 wt% (see supplementary information). This would render the vessels extremely resistant to high temperatures. In addition, Hessian fabrics contain 20–40 vol% of subangular or spheroidal quartz grains, resulting from the mixing of clay with sand. Non-plastic inclusions, notably quartz, can significantly increase the toughness and thermal-shock resistance of ceramics. As a result, a Hessian crucible would be less prone to cracking if struck while its contents were being stirred, or immediately after its removal from a hot furnace.

However, these factors are not exclusive to Hessian wares. We believe that a key stage in the manufacture of Hessian crucibles, which sets them apart from their competitors, was high-temperature firing in the potter’s kiln. Scanning electron microscopy and X-ray diffraction of unused Hessian fabrics reveal complete matrix vitrification and the presence of mullite and tridymite, which most probably crystallized from the decomposition of kaolinite at temperatures between 1,100 °C and 1,200 °C (refs 8,9).

These temperatures were unusual in Europe for firing pottery, with the exception of Rhenish salt-glazed stoneware, a product of the same region. A long, high-temperature prefiring would serve as a thermal-stability test for the crucible before delivery to the user. More important, this firing led to the formation of synthetic mullite (Fig. 1b,c), which we believe was the crucial secret behind the quality of Hessian crucibles.

Mullite (Al₂Si₂O₇) has been developed for a wide range of applications in modern ceramics, including for building and optical materials, and for thermal-protection systems and in liners for aircraft engines. Some properties of mullite relevant to its ancestral application are low thermal expansion (and a corresponding impressive thermal-shock resistance), high creep resistance, strength at high temperatures, and an outstanding stability in aggressive chemical environments.

The presence of interlocking acicular mullite in the ceramic matrix of Hessian crucibles would have conferred properties ideal for withstanding a range of thermal, mechanical and chemical stresses. It might even be argued that the scientific developments that led to the discovery of the elements and characterization of their thermochemical behaviour were only...
The taste of words on the tip of the tongue

Synaesthesia is a rare familial condition involving a ‘crossing’ of the senses — for example, ordinary activities such as reading or listening to music may be perceived with different colours or tastes. Here we show that individuals who experience synaesthetic tastes that are elicited by words (who are known as lexical—gustatory synaesthetes) begin to taste an upcoming word before they can actually say it (that is, while it is still ‘on the tip of the tongue’). Taste sensations in these synaesthetes are therefore triggered by thinking of the word’s meaning, rather than by its sound or spelling. It is possible that conceptual thought may even be linked to perceptual experience in all of us.

Brain imaging and inheritance patterns have established that synaesthesia is a genuine neurological phenomenon, but the psychological mechanisms that drive each manifestation are not yet fully understood. In the word—taste variant, pictures do not usually elicit a taste sensation without retrieval of the associated word, and tastes are triggered by the corresponding food name (for example, mince taste by the word mince) as well as by words that share phonemes with that food name (such as prince).

Given this phonological influence, it might be assumed that explicit processing of phonological word-forms (from auditory input, for example) is a necessary stage for stimulating synaesthetic tastes. Alternatively, taste could be experienced directly from the word’s meaning (that is, from abstract semantic information encoded in long-term memory, or its lemma). In this case, the role of phonology would be restricted to the stages in development when word—taste associations are being established (that is, determining which words become associated with which tastes), rather than serving to trigger the taste itself.

We investigated this second hypothesis by testing whether synaesthetic tastes could be induced in ‘tip—of—tongue’ (TOT) states, when only word meaning, but not the phonological word-form, is available for processing. Six cases with this rare type of synaesthesia were studied (for methods, see supplementary information). Each demonstrated the behavioural hallmark of synaesthesia by showing a significantly higher test—retest consistency over more than one year, compared with a control group tested after only two weeks (for details, see supplementary information).

In a TOT picture—naming task, the participants were shown images of unusual objects (a platypus, for example) to induce the TOT state, in which the word required was known but there was a temporary inabilty to recall it; they were then questioned about the ‘taste’ of the target word. Out of 550 trials, 89 induced a TOT state in which the synaesthete was striving to name the experimenter’s intended word. Seventeen of these were accompanied by anticipatory tastes, 15 of which occurred in a complete TOT state — where neither the word itself nor any constituent letters could be recalled.

In all instances, the anticipated taste corresponded to the correct taste of the target word, as verified afterwards by the participant (confirmation stage) and then again more than one year later in a surprise retest (see supplementary information). For example, one participant tasted tuna fish when the word castanets was on the tip of her tongue: she then named tuna as the taste associated with the spoken item castanets in the confirmation stage, and reproduced this same association in the surprise retest 1.1 years later.

The anticipated taste associations named in the TOT state are unlikely to have been spuriously generated, because the synaesthete experienced their correct anticipatory tastes significantly more often than would be predicted by chance (all P values less than 0.02), as estimated from the baseline frequencies with which each taste occurred for each synaesthete (for details, see supplementary information).

We conclude that perceptual experience, for these synaesthetes, is one component of the representation of the meaning of words. As synaesthetic taste can be induced in TOT states in the absence of phonological information, we propose a model in which pathways exist between word lemmas and taste centres. (Phonological factors may nevertheless developmentaly determine the nature of a taste — that is, the tastes associated with food names and their phonological neighbours.) These pathways may operate in everyone, but be exceptionally active in synaesthetes: other variants of synaesthesia (tone—colour, for example) are known to rely on universal cognitive mechanisms, and functional magnetic resonance imaging indicates that merely imagining a taste can activate the area of the normal brain associated with taste. Lexical—gustatory synaesthesia may therefore represent an exaggeration of normal mechanisms that link linguistic thought and sensory perception.

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