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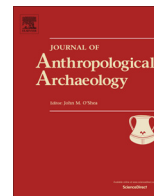
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# Production bias in cultural evolution: An examination of cubic dice variation in experimental and archaeological contexts



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## ABSTRACT

Similar artifact function and conformism to social norms are two models commonly proposed to explain why ancient people shared a particular form of material culture. We propose an additional model for explaining such similarity, *production bias*, which focuses on interactions between raw materials and the production of material culture. By way of modern replication experiments and a survey of ancient examples, we use dice to exemplify production bias and discuss how it can be recognized in the archaeological record. Although there are 15 possible configurations for cubic dice, all of equal function, only three are common in the archaeological record. Replication experiments show that one is the result of production bias, and is differentially produced by novice dice-makers. The other two are the byproduct of conformist cultural transmission processes. A similar result holds for dot patterns, or how dots are placed with respect to one another to represent a particular number.

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## 1. Introduction

Since at least the late 1800s, archaeologists have focused on explaining similarity in material culture between different archaeological sites, time periods, and/or regions. For example, the culture historical paradigm that dominated research in the early 1900s focused on similarity in material culture as a means to cross-date sites and trace historical relations of “cultures” over time and space (Lyman, 2000; Lyman et al., 1997). Material culture was typically interpreted as an assemblage of attributes that was inherited from previous generations that diffused over time and space in an unmodified or little-modified state. Similarity in artifact assemblages or artifact shape due to common descent is also referred to as “homologous” evolution.

Later research challenged some of these notions, suggesting that similarity in material culture could also be due to other, ahistorical, processes. Most archaeologists will be familiar with the argument that culture represents an “extrasomatic means of human adaptation,” after Binford (1962, see also White, 1959). In this respect, performance characteristics of tools within particular environmental constraints could explain why two tools appear similar in two different regions, with no historical connection.

For example, the reason that many hafted stone tips on projectiles have a triangular outline is due to the aerodynamics and the need for the tip to penetrate into the hide of, and cause damage to, an intended animal (or human) target. Evolutionary scientists typically refer to such similarity as the result of “analogous” evolution.

Dunnell (1978) attempted to consolidate and contrast these ideas by introducing the notion of style and function in the archaeological record. He suggested that artifacts shaped by function are subject to selective processes, while artifacts shaped by style are subject to random drift. Later research attempted to develop more formal and quantitative models to help archaeologists identify and isolate variation that is the result of functional or stylistic processes (e.g., Bettinger et al., 1996; Eerkens and Bettinger, 2008; Meltzer, 1981; Neiman, 1995; Van Pool, 2001). In general, stylistic processes generate new artifact variation, typically causing dissimilarity between regions or time periods, while functional processes tend to winnow variation, causing them to appear similar.

More recent models employ cultural transmission (CT) theory to explain similarity in artifact forms. Such models build on the culture historical and style-functional models of earlier research, and examine simultaneously the generation and winnowing of variation in material culture (Eerkens and Lipo, 2007). Within such models, similarity in material culture can be the byproduct of common culture history (or unbiased cultural transmission in CT terms) or performance characteristics (function or guided variation in CT terms). In addition, CT recognizes other processes, such as

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directly-biased and indirectly-biased transmission, which can cause similarity or dissimilarity. For example, [Bettinger and Eerkens \(1999\)](#) cite indirectly-biased processes as a means to explain similarity and dissimilarity in projectile points of the Great Basin, while [Shennan and Wilkinson \(2001\)](#) and [Kohler et al. \(2004\)](#) implicate directly-biased transmission processes, and conformist transmission in particular, to explain similarity and dissimilarity in pottery of Germany and the American Southwest, respectively.

This paper follows in that vein. We examine variation in two attributes of cubic dice: the configuration, or how numbers are arranged with respect to one another on the six faces of the cube, and dot patterns, or how dots are arranged with respect to one another to form a particular number. We focus our study on dice for three main reasons. First, assuming the numbers from 1–6 are placed on a cubic die, we can easily calculate all possible die configurations, or the potential attribute-state universe. This is often not possible with other artifact categories, such as pottery decoration, where there are nearly infinite attribute-state possibilities. As discussed below, there are 30 unique die configurations, which can be conflated to 15 when “mirror images” of particular forms are combined. Second, dice are known from a broad range of geographic and temporal contexts. As a result, we can examine variation in configuration in a range of different archaeological contexts. Third, dice are typically randomizing devices used in games to provide a level playing field. Provided each number appears only once on a die and the die is evenly weighted on all sides, it can be argued that different configurations and dot patterns are functional or performance equivalents. That is, there is no functional reason why a certain configuration or dot pattern should be preferred for randomizing the roll. This result allows us to focus our analysis of die variation on a more limited range of transmission processes.

## 2. Cubic dice

For the purposes of this article, we define cubic dice as roughly symmetrical 6-sided objects, with dots or numbers appearing on each side. In practice, the sides of dice may not be exactly equal in length, leading to varying degrees of asymmetry, and die edges may be rounded, leading to more ellipsoid rather than strictly cubic forms. As well, “false” dice with repeating numbers (e.g., a three appears twice to the exclusion of a five) are also present, but we do not include these in our analysis.

The (pre)history of cubic dice goes back to at least the third millennium bce when the first examples appear in the archaeological record ([Dales, 1968](#); [Moortgat-Correns, 1988](#)). It is generally thought that cubic dice were invented in the Indus Valley, within the Harappan civilization, and brought to Mesopotamian civilizations shortly afterwards, although evidence for their distribution is not complete and precise dating is unclear for many examples. As discussed below, the majority of the earliest Indian dice appear with a particular configuration of numbers that is different from modern dice (where the sum of numbers on opposite sides is seven). This ancient configuration is also common, for example, in early Etruscan sites ([Artioli et al., 2011](#)).

In Etruria, a different configuration (where opposite sides add to seven), begins to appear during the fifth century bce, and completely replaces the older configuration by the third century bce ([Artioli et al., 2011](#)). It is not until the Roman era that this later configuration becomes more widely used throughout Europe and parts of Asia and Africa ([Schädler, 2007](#)). This development may point to an independent invention in the Roman era, or more likely, borrowing of the general idea of cubic dice but with subsequent innovation or modification of the dominant Harappan

configuration style. Even though this “sevens” configuration (see below) appears at least once in the third millennium bce ([Dales, 1968](#)), the Romans seem to have made this configuration popular throughout the West, from where it was introduced to many other parts of the world.

The distribution of cubic dice is complicated by their varying contexts. Cubic dice compete with other randomizing technologies, including two-sided dice such as Egyptian throwing sticks and Indian cowry shells, four-sided dice such as astragals, oblong, and Westerwanna dice ([Kruger, 1982](#); [Finkel, 2004](#); [Schädler, 2007](#)), as well as other more-sided dice ([van der Heijdt, 2001](#)). They may have been associated with one or more games in which case they could have diffused along with game boards and other gaming materials, or they could have spread independently as part of games that were only played with dice with little need of other materials. For instance, several such games have been recorded for four-sided astragali used in Roman times ([Schädler, 1996](#)). As well, they may have spread by their association with divination or other religious practices, in which case they were not part of gaming at all. Contrary to game boards that are larger, carved in rock or played in the sand, dice are by definition small and portable. This facilitates the dispersal of dice without their original gaming (or non-gaming) context.

Dice require a common understanding of how they should be used, just as board games ([de Voogt et al., 2013](#)). Therefore, the transmission of dice should involve high fidelity, or careful copying, with low overall rates of error, experimentation, and innovation compared to other aspects of material culture. Thus, dice with numbers other than one through six are unlikely. It is unclear, however, whether this is true of the manner in which dots or numbers are placed on a die, in particular their configuration relative to one another on the die and the organization of the pips (e.g., are the dots of the three aligned diagonally, orthogonally, or in a triangular pattern). To date, the historical and archaeological record suggest that just a few configuration patterns and a few dot patterns have been used in history and prehistory and that they were prudently copied for millennia.

## 3. Die configuration and dot pattern

Readers may be familiar with the configuration of modern dice, which have opposite sides that add up to seven: 1 opposite 6, 2 opposite 5, and 3 opposite 4 (see [Fig. 1](#), top panel). For convenience we refer to this as the “Sevens” configuration. Of course, 1–6, 2–5, 3–4 is not the only possible configuration of numbers. A quick calculation reveals that there are 30 unique possible configurations for dice (see [Artioli et al., 2011](#)).

Although there are several ways to place the numbers one to six on a cubic die, many configurations mirror each other. Inverting the numbers that are on opposite sides is a trivial change for people using or making dice, but in most cases will follow the same production rule, such as “opposite sides add to 7.” For example, numbers can be placed 1–6, 2–5, 3–4, or 1–6, 2–5, 4–3 (where the position of the 4 and 3 have been inverted). These two forms follow the same “rule” (i.e., “opposite sides add up to 7”), but when a particular number is “up,” or showing (e.g., 1), and its pair is down (e.g., 6), the order of the remaining numbers (e.g., 2–3–4–5), read left to right, along the horizontal plane, varies. Both of these mirror-image configurations are found in dice today, even among factory-produced examples. Accounting for this small difference, this reduces the total number of possible configurations to 15 (see [Table 1](#)).

By contrast, many ancient hand-made cubic dice show a different configuration where the opposite sides are 1–2, 3–4, and 5–6 ([Fig. 1](#), middle panel). Since ancient dice producers did not write

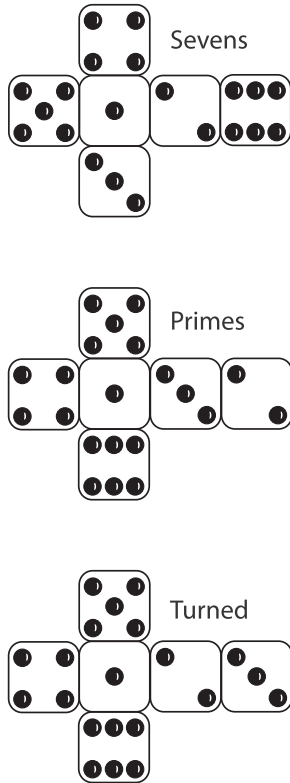


Fig. 1. Names of configurations used in the text.

down their methods for production, we cannot know the guiding “rule” they applied to arrive at this particular configuration. However, such a configuration is consistent with the rules that “sequential numbers appear on opposite sides” and “opposite sides add to a unique prime number.” In any case, this configuration is more common in dice found in archaeological sites in the Indus Valley and Mesopotamia (Dales, 1968; Rogersdotter, 2011), although examples with the Sevens configuration also exist in those areas (Moortgat-Correns, 1988). It is also common in Etruscan sites, especially those pre-dating 350 bce (Artioli et al., 2011), and Medieval Europe (Brown, 1990; Egan, 1997; Krauwer and Snieder, 1994), though in the latter context they are often found together with the Sevens configuration. Analogous to the Sevens configuration, we refer to this configuration as the

“Primes” configuration in reference to a possible rule of production.

The archaeological record demonstrates that configurations other than “Sevens” and “Primes” also exist, but that these are less frequent, as are dice on which numbers are repeated or have been replaced by figures or words. Fig. 2 shows a bar graph of different recorded die configurations, based on a sample of over 500 dice that pre-date ce 1800. They were taken from the literature (e.g., Artioli et al., 2011; Brown, 1990; Dales, 1968; Kruger, 1982), excavation reports (e.g., Portable Antiquities Scheme, 2013), or measured in museum collections in both North America and Western Europe. Only cubic dice with all the numbers 1 through 6 are included. The sample is certainly not random nor necessarily representative, but reflects a broad range of time periods and regions, including dice from Southeast and South Asia, the Middle East, North Africa, as well as Southern and Northern Europe. To be sure, certain regions and time periods are over-represented (e.g., NW Europe; Medieval). As well, this distribution does not characterize every region and time period, where instead, particular configurations are dominant. However, we feel the sample is sufficiently broad and diverse to represent a first approximation of worldwide variation in ancient die configuration.

As shown in Fig. 2, all die configurations are not equally represented. Instead, the figure shows the dominance of the Sevens configuration (on the right), and a notable peak for the Primes configuration (on the left). These two configurations were expected based on discussions in the literature (e.g., Artioli et al., 2011; Brown, 1990). Surprisingly, a third and more minor peak is also evident (configuration #4), which we discuss further below.

As argued above, functional arguments are unlikely to explain this non-uniform distribution of die configurations. Thus, a die with a Sevens, Primes, or any other configuration is not inherently better at randomizing the roll. From a purely functional perspective, then, we might expect all die configurations to be equally represented, and hence a more uniform distribution in Fig. 2. This is clearly not the case for cubic dice in antiquity, nor for cubic dice found today. Instead, we must turn to other explanatory frameworks to account for the distribution in die configuration, in particular, cultural transmission models. Below, we describe a set of experiments we carried out to establish a “neutral model” for the expected distribution in die configuration for individuals with little knowledge of, or experience with, dice.

During the experiments, we also examined the “dot pattern,” that is, the arrangement of dots that comprise a number. For example, the three dots that comprise the number three can be arranged in different ways, in a horizontal or vertical way, in a diagonal

Table 1  
Configuration occurrences in Experiment 1 and 2.

#	Configuration	Experiment 1	Experiment 2A	Experiment 2B
1	1–2, 3–4, 5–6	8 (4.2%)	1	7 (5.7%)
2	1–2, 3–5, 4–6	6		10
3	1–2, 3–6, 4–5	1		18 (14.6%)
4	1–3, 2–4, 5–6	79 (41.1%)	21 (67.7%)	4 (3.3%)
5	1–3, 2–5, 4–6	20 (10.4%)	1	11 (8.9%)
6	1–3, 2–6, 4–5	13		7
7	1–4, 2–3, 5–6	1	1	7
8	1–4, 2–5, 3–6	9		10
9	1–4, 2–6, 3–5	12	1	8
10	1–5, 2–3, 4–6	6		9
11	1–5, 2–4, 3–6	11	1	5
12	1–5, 2–6, 3–4	6	1	5
13	1–6, 2–3, 4–5	3		7
14	1–6, 2–4, 3–5	14 (7.3%)	2	8
15	1–6, 2–5, 3–4	3 (1.6%)	2	7 (5.7%)
	Total	192	31	123

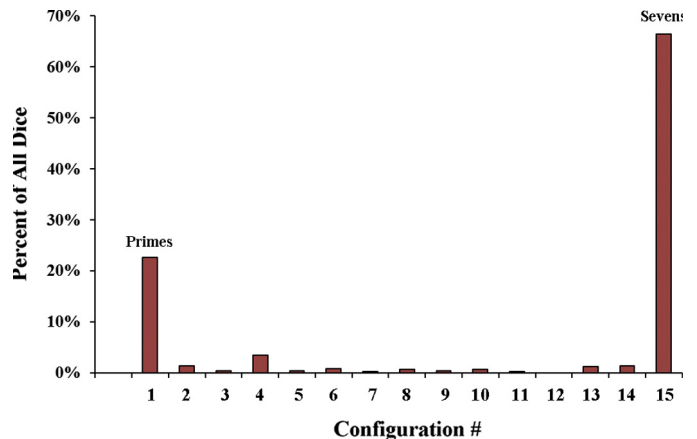


Fig. 2. Distribution of die configurations in a sample of ancient dice.

arrangement, or as a triangle. We had three individuals self-identify the three most common patterns for the numbers three, four, five and six for the dice produced in the experiments described below. That is, the three scorers were not told what comprises a distinctive dot pattern, they determined these after examining the dice. Although additional dot patterns are present, we focus here on just the two or three most common arrangements. We only included dice that had all six numbers present and recognizable, had each number from one to six once and only once, and maintained an overall (cubic) shape (see Fig. 3).

The distribution of dot patterns in the archaeological record was taken from 241 dice used in Medieval times in the United Kingdom

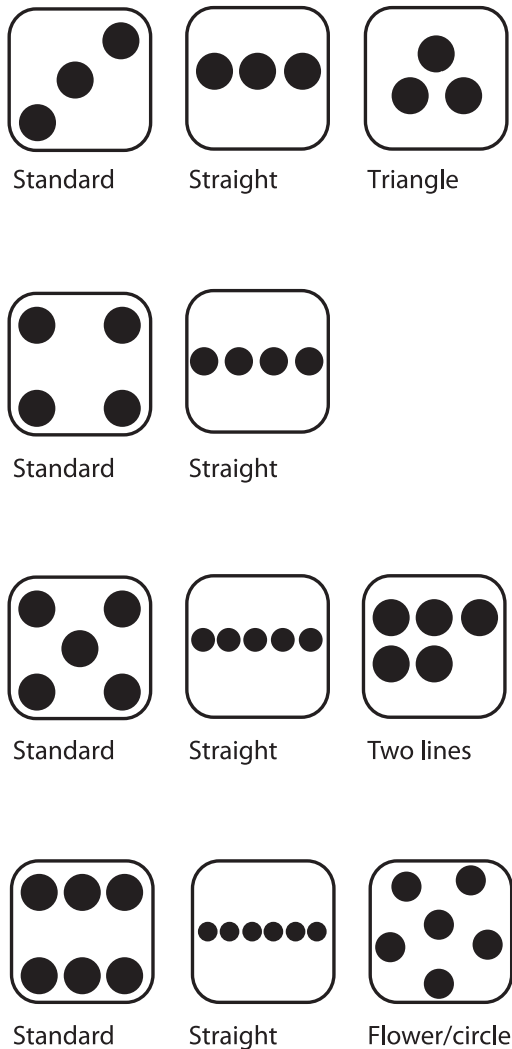


Fig. 3. Dot patterns.

and the Netherlands, a subset of the dice used in Fig. 2 that had been photographed from all angles and scored by one individual. Contrary to the dice from the experiment, the patterns are generally more carefully produced and easier to classify.

Most patterns in archaeological dice conform to those found on modern dice. However, as shown in Table 2, other patterns were also recorded, especially for the number three. Further, we note that non-standard dot patterns are not randomly distributed across the dice. Instead, when one number displays a non-standard dot pattern, other numbers are much more likely to be non-standard as well. Thus, six out of the nine dice with a non-standard four, five, or six also had a non-standard three. This suggests that die producers were either familiar with the standard patterns for all the numbers, or very few.

#### 4. Experimental reproduction

If we hypothesize that the configuration of numbers on a die was a random choice then the placement of dots on a die by dice producers should reflect an equal distribution across the fifteen relevant configurations shown in Table 1. On the other hand, if there are costs associated with die configuration (i.e., it is “easier” to produce certain forms), or if biasing cultural transmission processes act on this attribute, such as conformism, then one or more particular configurations may be preferred. For novice users and producers, we argue that cultural transmission biases should be non-existent (i.e., producers are not aware of the dominant or “correct” way to configure a die).

We test this hypothesis by means of an experiment where children and adults were asked to put the numbers one through six on an otherwise unmarked cubic die. Our first experiment focused on children under the age of seven because they are rarely familiar with the dominant configuration pattern of numbers on modern cubic dice, and hence are relatively uninfluenced by cultural transmission processes. Although a group of children is not equivalent to a random sample of novice dice manufacturers/users from antiquity, the production method of children is not influenced by particular preconceptions. Their age may influence their dexterity and thereby their ability to manipulate the dice in their hands when adding the dots but children are otherwise likely to configure the dots on a die in a near-random fashion. As well, the dot patterns could be randomly organized although their limited dexterity does not always make this organization clear. A second experiment focused on adults who had varying levels of knowledge about die configuration.

The experiments allowed us to examine different and related hypotheses regarding die production. The two experiments that follow aim to show that each configuration of the six numbers on a die have an equal chance of being produced when participants are unaware of the dominant configuration or dot pattern (i.e., have not been biased by cultural transmission processes).

**Table 2**  
Dot patterns identified in the archaeological record for dice from Medieval times in the United Kingdom and the Netherlands.

Pattern	Standard	Straight	Triangle	Two lines	Circle	Random	n/a	Total
3	207		12				9	241
4	231	13				1	9	241
5	230			7 <sup>a</sup>			4	241
6	230				1 <sup>a</sup>		10	241

Standard: the pattern found on modern dice; Straight: all the dots are placed in a straight line; Triangle, Two lines, Circle: description of other patterns; Random: irregular pattern; n/a: dots are not visible or present.

<sup>a</sup> The two lines pattern for the number 5 also showed a triangle (2×) or a straight (3×) pattern for the number 3 on the same die. The circle pattern for the number 6 also showed a triangle pattern for the number 3 on the same die.

## 5. Experiment 1

Three primary school classes in the Netherlands with a total of 67 children between the ages of four and six were asked to be part of this study. A total of 58 children were willing and able to participate. Permission from the school board, parents and the Institutional Review Board of the American Museum of Natural History in New York were obtained prior to the experiment.

The children's knowledge of cubic dice was briefly probed prior to starting the experiment but no specific knowledge of number configuration was found. The school director provided the age, gender and educational level of each child. The children were too young to show a preference for using the left or right hand so that handedness information was not considered a possible factor.

Each experiment consisted of two conditions in which participants were asked to make two dice (for a total of four dice per child). One condition had children sitting in a chair and the second had children standing in front of a table. The order of the two conditions was randomized as much as possible. Each condition had three children who were each given a pencil. As a group they were instructed to put all six different numbers on a die starting with the number one and going up from there. They subsequently received a cubic die made of soft clay, a type of material with which the children were familiar. The children were closely observed and instructed to start with a single dot before proceeding to two dots on a different side, three dots on the next and so forth. Although they observed each other to see how fast they were going and how the dots were placed on each side, they were independent in their choice of a side of the die. Each dot was produced by piercing the pencil into the soft clay. The instructor would repeatedly ask that they pick "another side of their choice" on which they wished to put the next number of dots. Children were assisted with counting the dots and with checking the final result.

The experiment was conducted in a separate room of a primary school during regular school hours. It was conducted in the presence of one experimenter who prepared and archived the dice and provided each group of three children with instructions (one group had one child only who was joined by her friend who had participated in a previous group). The dice were left to dry and then the results were recorded and entered into a database.

### 5.1. Experiment 1: Results

Fifty-one children completed at least three dice, i.e., they provided the clay die with the numbers one through six. "Incorrect" dice include those with an unreadable number of dots or with a

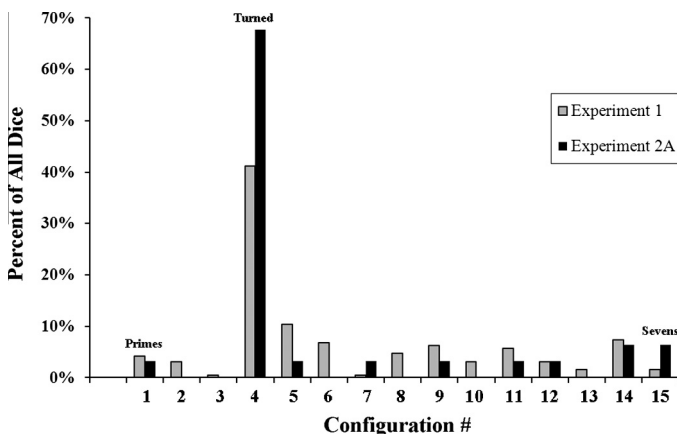


Fig. 4. Results of Experiments 1 and 2A, showing dominance of the "Turned" configuration.

repeated number, and were eliminated from the study. A total of 192 dice were produced that were suitable for analysis.

The final sample had 21 children from education level 1 (ages four and five years), and 30 children from education level 2, (ages five and six years). There were 30 boys (11 in level 1), and 21 girls (10 in level 1). Twenty-one children stood at a table first before moving to a chair and 30 did the opposite: the first condition had six children from level 1 and 13 boys of which four were from level 1; the second condition had eight boys from level 1.

Fig. 4 shows the distribution of dice produced in this experiment. Out of 51 children, the Sevens configuration of numbers 1–6, 2–5, 3–4 was used in only three cases and was distributed over three different individuals from different age, educational level and gender groups. Out of a total of 192, 79 dice showed the same configuration. This configuration, henceforth the "Turned" configuration, or 1–3, 2–4, 5–6, was used by 39 different children. Note that this configuration is produced if the numbers one through four are placed sequentially on faces of the die as the die is turned in a single plane, with the numbers five and six then placed on the two remaining sides. Twelve children used the Turned configuration at least three times of which nine children used this configuration exclusively. Twelve children did not use this configuration at all.

There was no significant difference between the number of times the Turned configuration was used in the first or in the second condition of the experiment ( $\chi^2 = 0.0008$ ;  $P = 0.98$ ;  $df = 1$ ). It was observed that children preferred to hold the die in their hand when applying the dots, both while sitting in a chair and standing at the table. As a result the table did not make a difference other than providing a reason for the experimenter to ask for another two dice. Forty-five of the 79 Turned configuration dice were produced by thirty boys, while 21 girls produced the remaining 34. Although girls used the Turned configuration more often than boys, this difference was not significant ( $\chi^2 = 0.32$ ;  $P = 0.057$ ;  $df = 1$ ). Also, there is no significant difference in the use of the Turned configuration between the 21 children from the first educational level, who used the Turned configuration 29 times out of a total of 75 dice, and the children from the second level ( $\chi^2 = 0.31$ ;  $P = 0.58$ ;  $df = 1$ ). It is noted that only twelve out of 21 children from the first level completed four dice while 27 out of 30 children in the second level group did the same and this was interpreted as an indication of improved manual dexterity.

A total of 159 dice were selected that had a recognizable dot pattern for the numbers three, four, five and six. Three individuals (scorers) self-identified the three most common patterns for the numbers three, four, five and six for the dice produced in the experiment involving the children. The three scorers were not told what comprised a distinctive dot pattern, but determined these after examining the dice. Although additional dot patterns were identified, we focus here on just the two or three most common arrangements.

The scoring results for the different dot patterns were generally similar. Although the scorers used different names, they all agreed on the three most common patterns for the numbers three, four, five and six. Importantly, the three scorers also agreed on which category had the highest count. It is this last aspect that will be important when we try to explain variation in dot patterns. Further, the standard pattern, that is, the pattern found in modern dice (i.e., diagonal line for three, square for four), was recognized for each number. Also, each number had a recognizable and often-found pattern in which all dots had been placed in a straight line. In addition, for the number three, a triangular pattern was common, for the number five, two lines of dots were common, and for the number six, a circle or flower-like pattern was occasionally recognized.

The experiment was conducted with three children at a time allowing the participants to copy dot patterns of their neighbors. The dexterity of the children varied so that even if a certain pattern was intended, the final arrangement could not always be identified as such. More importantly, the children's exposure to modern dice is likely to have included the pattern of the dots. The experiment was, therefore, less optimally controlled for the analysis of dot patterns than configuration. Despite these limitations, the results of the experiment show that patterns for the numbers four and six largely conform to that of modern dice while the patterns for the numbers three and five do not. This split between the even and uneven numbers when it comes to dot pattern variation is also found in the archaeological record.

## 6. Experiment 2

As discussed, experiment 1 did not lead to a random distribution of configurations. Since all participants of Experiment 1 were young children, a second group was asked to participate to compensate for a possible age or educational bias in the data. Thirty-one participants agreed to participate in an experiment approved by the Institutional Review Board of the American Museum of Natural History (AMNH), New York. At the end of the experiment they were asked age, education and gender information as well as their familiarity with the modern number configuration on cubic dice. Nine men and 22 women between the ages of 18 and 49 (average age 28) participated in the experiment. All were resident in the US, and were employed by or served as an intern or volunteer for the AMNH. With the exception of two, all participants held American citizenship. Each participant had finished a high school degree or equivalent. Ten people also held a BA, eight an MA, and one person had a PhD degree as educational background.

Each participant was asked to write the numbers one through six with a pen on a wooden unmarked cubic die, using Arabic numerals rather than dots. There were no additional instructions on how to place the numbers. In the first condition, one die was presented to see if the participant understood the initial instruction and also to give an indication of their familiarity with the modern number configuration on cubic dice. We refer to this as experiment 2A.

Two additional unmarked dice were then provided and the instruction was given to place the same numbers from one to six as randomly as possible on each side of the die. After completing these dice, the participants were given two more dice, and again, asked to place the same numbers as randomly as possible. However, it was made clear that it was no longer necessary to start with one and then add the numbers in order; they could add the numbers in any order they wished. The total of four dice that were produced "randomly" by each participant make up experiment 2B.

### 6.1. Experiment 2: Results

Each of the 31 participants created a total of five dice in experiment 2A and 2B combined. For experiment 2B two participants rolled the dice in order to choose a random side of the die. Several participants got confused in the second condition of experiment 2B, where they did not apply the numbers in sequence. They needed to check repeatedly which number(s) they had already added, and indeed, one participant created a die that lacked the number one but had two times put a number three on the cube; this die was corrected afterwards by the participant. None of the participants questioned the instruction of applying the numbers randomly on the die even though any configuration is, by definition, random from a mathematical point of view. Only seven participants admitted that they were familiar with the configuration of modern dice.

Results from experiment 2B are shown in Fig. 4. As expected, there is a more even distribution of configurations, including the Sevens and Primes configurations, that occur an equal number of times. The Turned configuration with four occurrences was less common than expected but not significantly so ( $P = 0.08$ ). One configuration, 1–2, 3–6, 4–5, had 18 occurrences, which is significantly more than expected ( $P = 0.001$ ). This result suggests that a more-or-less "random" distribution in die configuration can be produced, given the proper experimental conditions, although with one configuration still occurring more frequently. It is noted that this most common configuration in experiment 2B is one of the least common in experiment 1, experiment 2A, and in the archaeological record.

In experiment 2A (see Fig. 5), 21 of 31 participants (68%) produced the Turned configuration, including five people that were familiar with the Sevens configuration. This result is consistent with the results of Experiment 1, suggesting that there is a bias in die configuration when produced under these conditions.

## 7. Discussion

The results of the experiments help establish a context for understanding distributions in ancient die configuration. Rather than a uniform distribution of die configurations, a non-uniform distribution is present in both experimental and ancient examples. We argue that the different modes can be explained by different processes. We highlight three main points from the study below.

First, the experiments failed to produce significant numbers of dice with either the Sevens or Primes configuration. This suggests that the dominance of these forms in the archaeological record must be the byproduct of strong selective processes. As argued, these are unlikely to be selective in a functional sense, for example, due to superior performance, but instead must relate to biased

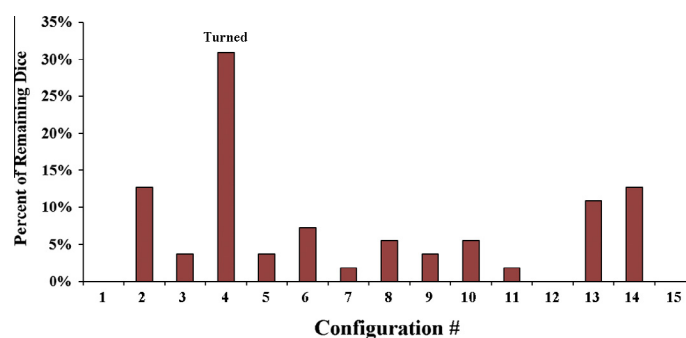


Fig. 5. Distribution of configurations in ancient dice, removing Sevens and Primes configurations.

cultural transmission processes. Dice require a common understanding of how they should be used, just as board games (de Voogt et al., 2013). As randomizing devices, they must also be judged to be “fair” among users. Using an agreed-upon or standardized form would remove one potential source of mistrust among consumers of dice, though it is possible to produce false dice even when holding a configuration constant (and examples of false dice are known from antiquity as well; see Spencer, 1985).

Once standardized forms emerge, transmission of information about dice involves high fidelity, or careful copying, with low overall rates of error, experimentation, and innovation compared to other aspects of material culture. Easy-to-summarize rules for die configuration, such as “opposite sides tally to seven,” “opposite sides add to prime numbers,” or “sequential numbers appear opposite one another”, are the most obvious choices for a particular standard, from a transmission perspective. As discussed elsewhere, fidelity in cultural transmission is highest when the complexity of information is lowest (Eerkens and Lipo, 2007). Such simple rules allow die makers and users to easily transmit information about die configuration, rather than developing a standard composed of a more arbitrary sequence of numbers that must be memorized, such as “1–2, 3–6, 4–5”. In hindsight, the dominance of just two configurations over more than 4000 years of human history supports the notion of strongly biased transmission governing the configuration of dice.

This finding holds true for dot patterns as well. Ancient dice are standardized compared to the diverse range of patterns produced by novices. More specifically, the experiments with school children failed to produce the dominant pattern identified in archaeological (and modern) dice for two of the four numbers included in the study (the three and five). Thus, instead of a diagonal line, which dominates archaeological examples, novices tend to produce a triangle for the number three. Likewise, instead of an “X” for the number five, novices tend to produce two lines. This suggests strong conformist transmission on dot patterns in antiquity.

Second, if we remove the dominant Sevens and Primes types from the archaeological dataset, and focus on the remaining examples (see Fig. 5), we are left with a distribution that appears very similar to the dice in Experiment 1 and 2A. One configuration, Turned, is the dominant form present (17 of 55 examples), being over twice as numerous as the next-most-common form (configuration #2 and #14 in Table 1 with 7 out of 55 examples each). The probability that a binomial random variable with parameters  $n = 55$  and  $p = 1/13$  takes a value greater than or equal to 17 is 0.0000005. In other words, the Turned configuration is found far more often than would be expected by chance alone. As opposed to our explanation for the Sevens and Primes configuration, however, we do not think that cultural transmission factors account for this mode.

Note also that configurations #7 and #13 are extremely rare among archaeological examples, with only 1 of the former and none of the latter ( $P = 0.07$  and  $P = 0.01$ , respectively). These configurations were rare in experiments 1 and 2A as well, suggesting that some set of factors conspire against the production of these particular forms.

This same general finding also holds among dot patterns. Ignoring the dominant pattern from the archaeological dice and focusing on the remaining forms, the archaeological dice produce the same general patterns found among the experimental dice from novices. For example, for the number three, the second and third most common patterns in the archaeological dice (straight line and triangle) are the most common forms among the novices, and for the number five, the second most common form among the archaeological dice (two lines) is the dominant arrangement produced by novices. This is also reflected in the number six, where the only archaeological example that was not of the dominant

pattern was the second most common pattern among novices (flower/circle). We also note that the number three stands out both in the experiment and in the archaeological record as showing the greatest amount of dot pattern variation.

Third, the experimental results show that when individuals who have little prior knowledge or experience with die configuration attempt to place the numbers one through six on a cubic object, without further instruction, the turned configuration emerges as dominant. Two additional, but more minor modes are also evident in the experimental data, and follow a similar sort of rotational logic. Configuration #5 (1–3; 2–5; 4–6) results if the numbers 1–2–3 are placed sequentially along one rotational axis (a 3/4 ring around the cube), and the remaining 4–5–6 are then placed sequentially along a second rotational axis (a second 3/4 ring). Likewise, configuration #14 results if a one is placed on one side of the cube, for example the “up” position, then two through five are placed along a single axis of rotation, or around the sides of the cube, and the 6 is placed on the remaining or “down” face. As with the Turned configuration, these two configurations (#5 and #14) rely on placing numbers sequentially on adjoining sides of the cube while turning it in just two directions. In this manner, it is easy for a die maker to ensure that all numbers appear on the cube just once. Note that if the numbers one through six are applied sequentially for either the Sevens or Primes configuration, that the producer must both skip faces while applying numbers, and rotate the die in a number of different directions. Although configuration #5 is uncommon in the archaeological examples, note that configuration #14 was also the fourth most-common type in the ancient examples (behind Sevens, Primes, and Turned).

We suggest then, that the Turned configuration, as well as the triangle dot patterns for the number three and the two lines dot pattern for the number five, is not the byproduct of either functional processes or cultural transmission biases, such as conformism. Instead, we argue that these forms are the byproduct of a *production bias*. We define this term as a bias that emerges from the production process itself (versus bias resulting from use), thereby restricting potential variation in an artifact or technology. This bias may be a byproduct of reducing the amount of energy or time required to produce a particular item, relative to other forms, or from simplifying the instruction set needed to produce a particular item. Producers may or may not be consciously aware of these properties. In any case, lacking other instructions, such as the need to conform to a socially accepted or functionally superior form, production bias will lead to a non-uniform distribution of types or forms in the archaeological record. This non-uniform distribution can hold even when different forms or types have equal performance characteristics, that is, equivalent functional properties, as is the case with randomizing devices like cubic dice.

Production bias may act to lower the frequency of certain other forms. Among dice, we suggest production bias selects against configurations #7 and #12. To make a die with these configurations while applying the numbers sequentially, the producer must make several rotations of the cube and skip over certain faces. Furthermore, to the best of our knowledge, the numbers on opposite sides do not follow a simple rule that die-makers could apply. The complexity of these configurations, then, selects against their production among novice and skilled die-makers.

Production bias is similar to, but distinct from, related processes such as skill acquisition (Bamforth and Finlay, 2008; Bleed, 2008; Stout, 2002) and the learning of crafts. Production bias should be especially present and measurable among novice producers of a particular item or technology (see Ferguson, 2008), but may persist even among experts. It will be especially prevalent in social learning contexts where people attempt to produce a particular end product (i.e., emulation), but are less familiar with all the steps



**Table 3**

Dot patterns identified in experiment 1 by scorer A, B and C. The modal pattern is in bold.

Pattern	Standard (A/B/C)	Straight (A/B/C)	Triangle (A/B/C)	Two lines (A/B/C)	Flower/Circle (A/B/C)	Other (A/B/C)	Total
3	26/21/21	32/49/47	<b>87/89/89</b>			14/0/2	159
4	<b>98/100/90</b>	23/25/21				38/34/48	159
5	42/40/37	14/14/14		<b>63/71/59</b>		40/42/49	159
6	<b>77/93/87</b>	7/9/7			28/17/11	47/40/54	159

Standard: the pattern found on modern dice; Straight: all the dots are placed in a straight line; Triangle, Two lines, Flower: description of other patterns; Rest: remaining patterns that could not be grouped in sets larger than the other categories or that were considered 'random'.

during production (i.e., “imitation”; see Caldwell et al., 2012). In this respect, manufacturers focused on emulation may be less aware of the specific steps they take to reach that end, allowing a production bias to introduce some degree of standardization.

Skill acquisition (guided variation) and/or social learning (cultural transmission) may override the effects of production bias. Thus, artisans may need to conform to particular norms (e.g., conformist transmission), or through experience, may acquire a preference for other forms or modes (e.g., guided variation) that are different from the production bias. As such, the strength of production bias may vary depending on particular learning contexts and conditions during craft production.

We believe that production bias is likely to be present in a wide range of pre-industrial human technologies. For example, a preference for right-handedness among humans may lead to a production bias. If handedness affects artifact shape or form, and the majority of producers are right-handed, then the dominance of a particular artifact form could be explained by such a production bias, rather than biased cultural transmission or superior tool function. Such biases have been proposed to hold among ancient flintknappers among otherwise functionally-equivalent stone tool forms (Steele and Uomini, 2005) and among cordage producers among functionally-equivalent twist directions (S- versus Z-twist; Emery, 1952). Similarly, in the history of writing systems we find left-handed and right-handed scribes, e.g., for Mayan hieroglyphs (Boot, 2003), but the cuneiform stylus strongly favors right-handed people when cuneiform is written from left-to-right (Taylor, 2011:14). Investigations of the Northwest Semitic script traditions of the first half of the first millennium bce have shown “that script changes up to seemingly different ‘national scripts’ depend almost exclusively on changes in the scribe’s hand and the scribe’s attitude” (Lehmann, 2012:85; van der Kooij, 1986). Informal experiments with students who were asked to attain specific scribal attitudes when producing letter types showed that these attitudes would lead to the production of visually different scripts known from antiquity (Lehmann, 2012, pers. comm.). We believe that production bias will also be present in other ancient technologies, such as pottery, but additional experiments with novices will be necessary to identify the nature of such biases.

In general production bias is difficult to confirm without experimental evidence that reproduces the biased results among novices who are not familiar with a functionally superior or socially acceptable mode. Even in dice production, the experimental results came as a surprise and would be difficult to predict from the archaeological record alone.

As can be gleaned from Table 3, novice die producers still generate the standard dot pattern for the numbers four and six. This was found by each of the three scorers and the effect is large. While we might be tempted to attribute the minimal variation in dot patterns for these numbers in the archaeological dice to strong conformist transmission, the results from novice dice producers suggests that production bias is an equally viable explanation. The interaction of the novice with the cubic clay material has led to a clear preference in dot arrangement, one that is also present in ancient examples. By contrast, the strong modal dot patterns

for the numbers three and five in the ancient dice are more likely to be the byproduct of production bias.

## 8. Conclusions

We argue that the concept of *production bias* can be used to explain certain modes in artifact form. Recognition of this concept is important because a repeated occurrence of a particular form or configuration in an artifact, when many options are available, is often ascribed to either superior performance characteristics or to biased cultural transmission (Boyd and Richerson, 1985), sometimes also referred to as function or style (Bettinger et al., 1996; Dunnell, 1978). However, production bias is not functional in the sense that the artifacts produced are superior in their performance characteristic(s), nor are these items the byproduct of copying, stylistic processes, or biased cultural transmission. Instead production bias emerges from the interaction between humans and a medium during the production process itself.

Although there are 15 possible configurations for the placement of numbers on cubic dice, all of equal performance quality in generating a random number, the archaeological record shows a non-uniform distribution. Ancient dice show a tri-modal distribution in configuration, though the height of the modes varies markedly. A single configuration dominates ancient dice, Sevens, a form that continues to be used today. A secondary mode was especially common in ancient India, Etruria and Medieval Europe, but is no longer common today. A third mode is minor, but also clear in the archaeological data. This last mode, however, emerges as dominant among novice die manufacturers in experimental replication. That is, people who have not acquired the necessary cultural information through transmission about a “proper” die configuration tend to produce this form. We refer to this as the Turned configuration, and suggest it emerges from a production bias.

It is somewhat beyond the scope of this paper, but we note that dice with Turned configuration in the UK and the Netherlands are nearly all made out of metal (copper- and especially lead-based alloys), while metal dice account for a minority of the dice in our database. No bone or ivory dice display this configuration, the most common raw material for ancient dice. As well, the majority of the Turned-configured dice are medieval in age. It remains a hypothesis to be tested in future research, but medieval metal smiths with little prior knowledge of die configuration (i.e., novice die-makers) may have been responsible for producing these Turned examples. Future research regarding the particular archaeological contexts of these Turned dice could help address this issue.

Although there are many possible dot patterns for dice, a few are preferred by novice dice users. Some of these are identical to modern and ancient dice patterns, but others are clearly not. They suggest that *production bias* is not limited to three-dimensional number configurations, but is also found for two-dimensional stylistic patterns. Significantly, such bias is likely to be present elsewhere in the archaeological record as well, for example in three-dimensional forms or decorative patterns on pre-industrial products such as baskets, pots, or rock art.

Replication experiments, as undertaken here, can identify the direction of a potential production bias. Examining production patterns among novices is useful, especially if variation is reduced or if particular forms are more common than expected, relative to experienced producers. As with interpreting variation in any artifact type, providing a context, including the production phase, is essential to understanding the end product visible in the archaeological record.

In sum, we suggest production bias is an important concept for understanding variation in ancient material cultures. Prior to ascribing superior functional characteristics and/or implicating a biased cultural transmission process, investigating potential sources of production bias will aid our understanding of ancient technologies. As we have shown here, production bias can account for at least one of the three modes of die configuration in ancient dice, and possibly two of the dot patterns on modern dice.

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