

RESEARCH ARTICLE

Primes Do Not Pay

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ABSTRACT

We examine the role of prime numbers in conscious selection, the mental process by which players select numbers non-randomly on a lotto ticket. Using three estimators of the popularity of numbers, we show that the tendency to overselect prime numbers significantly reduces individual gains. We use 10 years of public data from the Belgian National Lottery to demonstrate our main result and to test the robustness of our findings against several confounding factors such as the tendency to play birthday dates and the preference for “lucky” numbers. Evidence from two independent survey data sets corroborates our main finding.

1 | Introduction

Bounded rationality, a term coined by Herbert Simon, refers to the limited cognitive abilities of humans in decision-making processes (Simon 1957). In the context of gambling, particularly lottery participation and number selection, players exhibit a behavior that deviates from the traditional model of rational choice. They often rely on heuristics and exhibit cognitive biases, which lead them to adopt suboptimal strategies.¹ The literature on lottery gambling has repeatedly demonstrated that, despite the randomness of official lottery draws, players do not select their numbers at random (Cook and Clotfelter 1993; Papachristou and Karamanis 1998; Simon 1998; Farrell et al. 2000; Roger and Broihanne 2007; Baker and McHale 2009; Turner 2010; Baker and McHale 2011; Wang et al. 2016; Polin et al. 2021; Roger et al. 2023). This behavior, termed “conscious selection” by Cook and Clotfelter (1993), is often linked to superstitious beliefs (e.g., selecting ‘lucky’ numbers) or specific number combinations (e.g., birth dates). In many Western countries, 7 is perceived as a lucky number and is thus frequently overrepresented in lottery selections (Roger 2011; Wang et al. 2016; Polin et al. 2021; Roger et al. 2023). Players can also be vulnerable to conscious selection² because they bet on birthday dates

(D’Hondt et al. 2024) or show preferences for certain number combinations.³

Since lotto draws are random by nature, all combinations are equally likely to appear in the official draw. It follows that the use of specific heuristics is not, at first glance, a proof of bounded rationality.⁴ However, lotto games obey the parimutuel principle, meaning that the prize pool is shared among winners according to prespecified rules. Therefore, the use of common heuristics to select numbers dilutes potential payouts and results in lower-than-expected returns, because of the parimutuel principle; more winners imply lower individual prizes.

In this paper, we analyze a specific form of conscious selection, namely the preference of lotto players for prime numbers. We show that lottery players tend to bet on prime numbers more frequently than what would be expected under random selection, a behavioral bias that significantly lowers expected gains. We note, however, that “conscious selection” does not imply that this preference is itself deliberate.⁵

Our analysis covers 1044 draws of the Belgian 6/45 lotto game between 2014 and 2023.⁶ On average, 595,343 players participated

in each draw,⁷ corresponding to approximately 3.7 billion tickets purchased over the period.

Using three different measures of number popularity, we find that players bet more on prime numbers than what is expected under random choice. We show that this result is not a by-product of the birthday date effect (Farrell et al. 2000; D'Hondt et al. 2024), or of the (lucky) number 7 effect (Roger and Roger 2025), and it is robust to controlling for the day of the week and the number of tickets per player. We demonstrate this finding both for the numbers in the main draw and the bonus number. We further show that, because of the parimutuel principle, players who favor prime numbers earn significantly lower gains. A grid containing five primes can reduce gains by up to 31.42% compared with a grid containing fewer than five primes.

We reinforce our findings using two independent data sets based on survey responses.⁸ Using the complete information on number choices by participants in the two samples, we confirm that respondents disproportionately select prime numbers.

Our paper contributes to the literature on conscious selection in lottery games, which documents systematic departures from random number choice. Prior work can be organized around three broad mechanisms. The first concerns personally meaningful numbers, most notably the birthday effect, which leads players to overselect numbers below 31 (Farrell et al. 2000; Roger and Broihane 2007; D'Hondt et al. 2024). The second concerns culturally salient numbers, such as the preference for 7 in Western countries (Roger 2011; Wang et al. 2016; Polin et al. 2021; Roger et al. 2023), and more generally superstitious associations with specific digits. The third concerns heuristics related to the perception of randomness, including the avoidance of visually structured combinations (Ladouceur et al. 1995; Hardoon et al. 2001; Krawczyk and Rachubik 2019) and responses to past outcomes through the hot-hand and gambler's fallacy (Clotfelter and Cook 1993; Suetens et al. 2016; Kong et al. 2020). A common feature of these mechanisms is that they rely on *extrinsic* properties of numbers, such as personal relevance, cultural meaning, or perceived patterns across combinations. By contrast, the role of *intrinsic* mathematical properties has received little attention in the lottery context.

We focus on one such property, primality. Prime numbers form a well-defined mathematical category, introduced early in schooling and widely recognized outside specialist contexts.⁹ Primality does not map directly into the mechanisms above: Primes are not systematically small, are not consistently associated with luck, and do not generate simple visual patterns over the relevant range.

Our contribution is twofold. First, using 10 years of aggregate lottery data and two independent survey data sets, we document that players overselect prime numbers. This pattern is robust to controls for standard heuristics, including salient and commonly selected numbers. Second, we show that this behavior has economic consequences. Under the parimutuel structure, combinations with a high share of primes yield returns that are up to 31% lower than combinations with few primes. In addition, we show that numeracy is strongly associated with the propensity to select primes, consistent with an interpretation in which prime

numbers are overselected as a result of their primality rather than other commonly proposed explanations such as salient or familiar number patterns.

2 | Lotto Games

2.1 | General Presentation

Playing a lotto game consists of betting on a combination of n numbers from $N \gg n$, without replacement. In our empirical analysis of the Belgian Lotto, $n = 6$ and $N = 45$ meaning that players notch 6 numbers on the lotto ticket. However, when the official draw takes place, n numbers are drawn at random and b bonus numbers are added to the main draw ($b = 1$ in our study but in some games, such as the Euromillions lottery, $b = 2$). The official draw of a standard lotto game is characterized by the triple (N, n, b) . The bonus number(s) can be drawn from the set of the remaining $N - n$ numbers after the main draw (as in the case of the Belgian Lotto) or from an independent set of numbers (as in the case of the Euromillions lottery). In summary, in this paper, we will focus our attention on the Belgian Lotto game which is characterized by parameters $(N, n, b) = (45, 6, 1)$. However, it is important to remember that players do not bet separately on the bonus number. The jackpot is won with all 6 correct numbers on the ticket (the bonus number is irrelevant for the jackpot win), therefore the number of combinations is $C(45, 6) = 8, 145, 060$.¹⁰

Lotto games obey the parimutuel principle, which applies as follows. First, a takeout rate is applied to the global amount of bets. For the Belgian Lotto, this takeout rate is variable because the last three ranks pay fixed prizes, as shown in the last column of Table 1. The remainder, denoted M , is redistributed to the winners, according to prespecified sharing rules over a set of winning ranks.¹¹ Table 1 shows the requirements for each of the 9 winning ranks along with the corresponding probabilities of winning (Column 3). For example, winning at rank 5 means that the ticket has four correct numbers without the correct bonus number. As the amount M to be redistributed is shared across the nine ranks, with a given percentage of M devoted to each rank, more winners at a given rank means lower individual prizes at this rank.

The game was launched in February 1978 and has undergone many changes since then. For our study period (2014–2023), the most important change was the introduction of a ninth winning rank on May 26, 2018. Winning at this rank means that the player has one correct number plus the bonus number. Winners at the ninth rank get a fixed prize equal to the current ticket price (€1.25). The ticket price was €1 before the introduction of the ninth rank.

2.2 | Data

2.2.1 | Main Data Set

Our main data set comes from the official website of the Belgian National Lottery.¹² We extracted data from 1044 draws that took place over a complete 10-year period from January 1, 2014, to December 31, 2023. For each draw, we collected the following

TABLE 1 | Winning combinations, probabilities of winning for each rank, and percentages of redistribution of bets.

# winning combinations		Winning probability	Percentage/amount distributed
Rank 1 (6+0)	1	1.2277×10^{-7}	17.50%
Rank 2 (5+1)	6	7.3664×10^{-7}	2.95%
Rank 3 (5+0)	228	2.7992×10^{-5}	2.80%
Rank 4 (4+1)	570	6.9981×10^{-5}	1.40%
Rank 5 (4+0)	10545	1.2946×10^{-3}	2.59%
Rank 6 (3+1)	14060	1.7262×10^{-3}	1.38%
Rank 7 (3+0)	168720	2.0714×10^{-2}	€6.25
Rank 8 (2+1)	126540	1.5536×10^{-2}	€3.75
Rank 9 (1+1)	442890	5.4375×10^{-2}	€1.25

Note: Column 1 reports the structure of the 9 winning ranks where $(k_c + k_b)$ means k_c correct numbers in the main draw and k_b correct bonus numbers ($k_b = 0$ or 1). Column 2 gives the number of winning combinations and Column 3 the probability of winning which is the number of combinations of Column 2 divided by the total number of combinations (8,145,060). Finally, Column 4 indicates the percentage of bets redistributed to winners for ranks 1 to 6 and the fixed prizes paid at the lowest ranks. Over our sample period, there was an important modification: A ninth rank of gain was introduced on May 26, 2018. This ninth rank (1 correct number plus the bonus number) pays a fixed amount equal to the ticket price, which is currently €1.25 (€1 before May 26, 2018). Using the same notations as before, the equation below provides the probability of winning with k_c and k_b correct and bonus numbers (with $k_c \leq 6, k_b \leq 1$ and $k_c + k_b \leq 6$).

$$P(k_c, k_b) = \frac{C(n, k_c) \times C(N - n - k_b, n - k_c - k_b)}{C(N, n)},$$

where $C(N, n)$ is the number of combinations of n numbers out of N without replacement.

variables: (1) the date of the draw (and therefore the day of the week); (2) the numbers that were drawn, including the bonus number; (3) the total amount of bets; (4) the number of players; (5) the number of winners at each rank; and (6) the corresponding individual prizes. We use data from the Belgian National Lottery because it is one of the few lotteries that publicly provides the global amount of bets and the number of players.

2.2.2 | Alternative Data Sets

To complement our main analysis, we also use two alternative data sets, from published studies based on surveys (Roger et al. 2023; D'Hondt et al. 2024).¹³ In both surveys, participants completed two 6/45 virtual lotto tickets consecutively. The first includes 489 Belgian respondents (Roger et al. 2023) and the second 498 (D'Hondt et al. 2024). Both questionnaires were administered by Qualtrics, which selected participants to be representative of the Belgian population in terms of gender, income, and age. These data provide granular information on individual number choices, allowing us to observe the exact composition of each ticket.

2.3 | Descriptive Statistics

In this subsection, we provide descriptive statistics about our main data set. Panel A of Table 2 provides statistics on bets. On average, 595,343 players participated in each draw. They spent an average of 4 million euros, which corresponds to €5.8 per player per draw. A ticket cost €1 until May 23, 2018, when the price increased to €1.25, where it has remained since. Panel B of Table 2 focuses on the characteristics of the draws. Not surprisingly, given the large number of draws and their random nature, the

reported statistics are close to what is expected under random choice. The average of drawn numbers (23.11) is not different from the expected value of 23 in a 6/45 lotto game ($t = 0.7336$, $p = 0.4634$). There are 14 prime numbers (2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41, 43) that can be drawn among the 45 numbers. It follows that the expected number of primes in a draw is equal to $6 \times 14/45 = 1.866$. Our sample average is equal to 1.82, not significantly different from 1.866 ($t = -1.3300$, $p = 0.1828$). For the bonus number, the theoretical proportion of prime bonus numbers is $14/45 = 0.311$ not significantly different from the observed proportion of 0.302 ($t = 0.6604$, $p = 0.5092$).

As we control the prime number preference for potential confounding effects, we check that the control variables we use are not biased in the sample of 1044 draws. For example, there are, on average, 1.3352 odd numbers per ticket that are not prime numbers (rounded to 1.34 in Table 2). The expected number under random choice is $(23 - 13) \times 6/45 = 1.33$ because, out of the 14 prime numbers, 13 are odd, leading to $23 - 13 = 10$ non-prime odd numbers in the set of 45 numbers. The difference between the observed average and the expectation is negligible ($t = 0.0638$, $p = 0.9491$). Finally, the sample has an average of 3.98 numbers less than or equal to 30 per draw, with an expected value equal to $6 \times 30/45 = 4$; the difference is not significant ($t = 0.5624$, $p = 0.5740$). In addition to the previous statistics, Figure 1 provides the frequency of occurrence for each number between 1 and 45 over the 1044 draws. Non-prime numbers are in blue, while prime numbers are in grey. Overall, prime numbers are neither over- nor under-represented in the draws. The statistics provided in Table 2 and the visual inspection of Figure 1 show that our sample is not biased.

In Table 3, we examine the distribution of prime numbers in the sample instead of focusing solely on the average number of prime

TABLE 2 | Summary statistics of the Belgian Lotto game: 2014–2023 (1044 draws).

Panel A: Statistics on bets					
	Mean	Median	Standard deviation	Minimum	Maximum
Overall bet	3986660.27	4404242.38	1296490.48	2088777.00	8324598.75
# players	595343.36	632392.00	153819.81	361014.00	1000140.00
# tickets sold	3524365.35	3694550.50	1189963.99	1806075.00	7643020.00
# tickets per player	5.81	5.79	0.56	4.87	7.64
Panel B: Statistics on the distribution of drawn numbers					
	Mean	Median	Standard deviation	Minimum	Maximum
Mean number drawn	23.11	23.17	5.05	7.83	38.50
# prime numbers	1.82	2.00	1.07	0.00	5.00
# prime bonus	0.30	0.00	0.46	0.00	1.00
# non-prime odd numbers	1.34	1.00	0.97	0.00	4.00
# of Numbers ≤ 30	3.98	4.00	1.10	0.00	6.00

This table presents summary statistics of the lotto game over 2014–2023. *Overall bet* is the revenue per draw generated by ticket sales, *# players* is the number of players in each draw, *# tickets sold* is the number of tickets sold, *# tickets per player* is the average number of tickets per player in a draw, *Mean number drawn* is the average of numbers drawn over the study period, *# prime numbers* is the number of prime numbers in a draw, *# prime bonus* is a dummy equal to 1 if the bonus number is prime, *# non-prime odds* is the number of odd numbers that are not prime per draw, and *# of Numbers ≤ 30* is the number of numbers less than 30 in a draw.

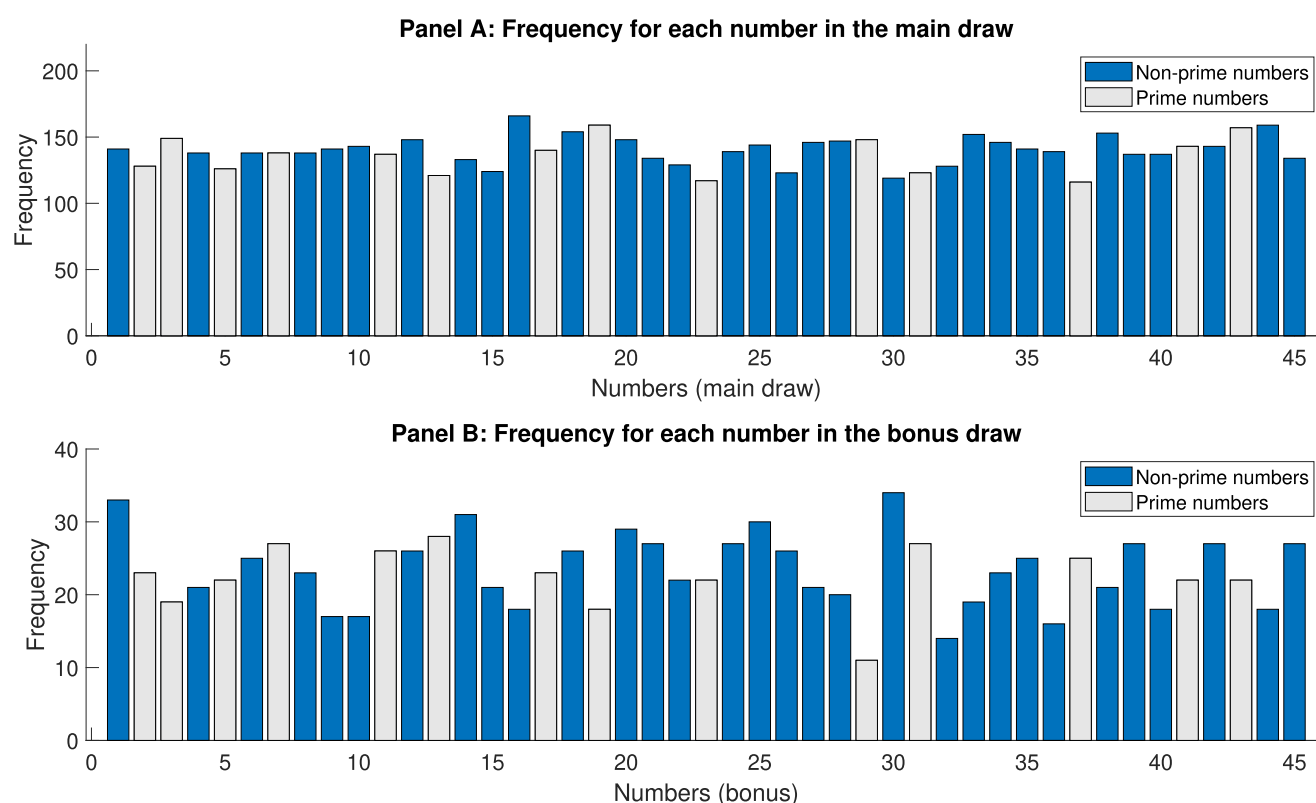


FIGURE 1 | Frequency of numbers drawn. *Note:* This figure provides the frequency (in number of draws) for each number between 1 and 45 in the main draw (Panel a) and in the bonus draw (Panel b). Prime numbers appear in gray while non-prime numbers appear in blue. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

TABLE 3 | Distribution of prime numbers.

	Theoretical	Empirical	Statistics
0 prime number	94.37	100	
1 prime numbers	304.90	323	$\chi^2 = 4.0488$
2 prime numbers	367.01	361	
3 prime numbers	209.72	190	p-value = 0.6701
4 prime numbers	59.66	63	
5 prime numbers	7.95	7	
6 prime numbers	0.38	0	

Note: The first column contains the different possibilities for the number n_p of prime numbers in the draw. The second column gives the theoretical number of draws with n_p prime numbers. It is calculated by multiplying $P(n_p, n, N_p, N)$ by 1044, the total number of draws. The probability $P(n_p, n, N_p, N)$ of getting n_p prime numbers in a draw where n numbers are drawn in a set of N numbers including N_p prime numbers is:

$$P(n_p, n, N_p, N) = \frac{\mathbf{C}(N_p, n_p) \mathbf{C}(N - N_p, n - n_p)}{\mathbf{C}(N, n)},$$

where $\mathbf{C}(m, j)$ is the number of combinations of j numbers out of m without replacement. The third column gives the observed frequencies and the last column provides the value of the χ^2 test and the corresponding p -value.

numbers as in Table 2. That is, we consider the entire distribution of the number of primes across draws and we compare it to the theoretical distribution. In the Belgian Lotto game, players choose numbers between 1 and $N = 45$; there are $N_p = 14$ prime numbers lower than $N = 45$. Players fill out their ticket with $n = 6$ numbers, and the official draw contains n_p prime numbers where n_p takes values from 0 to 6. The possible values of n_p appear in the first column of Table 3. The second column is obtained by multiplying the number of draws in the sample, namely 1044, by the probability $P(n_p, n, N_p, N)$ that a draw contains n_p prime numbers where $P(n_p, n, N_p, N)$ is defined as follows:

$$P(n_p, n, N_p, N) = \frac{\mathbf{C}(N_p, n_p) \mathbf{C}(N - N_p, n - n_p)}{\mathbf{C}(N, n)}. \quad (1)$$

Table 3 shows that there is no significant deviation with respect to the distribution of primes in random draws. ($\chi^2 = 4.0488$, $p = 0.6701$).

Table 4 provides detailed information on the number of winners per rank. We observe a large variation between the minimum and the maximum number of winners at each rank. The first explanation for this heterogeneity is the amount of tickets sold. Indeed, sales are strongly driven by the jackpot amount. A high jackpot prize (after several rollovers for example) attracts additional players and/or leads existing players to buy more tickets. Mechanically, this gives rise to a larger number of winning tickets. The second explanation for the heterogeneity in the number of winners is conscious selection. Since some numbers are more popular than others (e.g., numbers lower than 30, see Boland and Pawitan 1999; Otekunrin et al. 2021; Turner 2010; Wang et al. 2016), the number of winners is strongly linked to popular numbers being present in the draw. This is the reason why measuring the popularity of individual numbers is important.

2.4 | Measures of Number Popularity

As mentioned above, a draw that includes popular numbers leads to a substantially higher proportion of winners, relative to the expected number of winners under random selection. To measure the popularity of a given number in our sample, we build on the popularity index developed by Roger et al. (2023). The modifications we introduce are justified by the differing objectives of the two studies. While Roger et al. (2023) investigated variations in the popularity of a specific number (19) over time, our analysis focuses on comparing the popularity across different subsets of numbers, specifically primes versus non-primes.

The main draw of six numbers and the bonus number draw require a different treatment. For the main draw, it is sufficient to calculate the aggregate proportion of winners across all ranks excluding the bonus number, that is, ranks {1, 3, 5, 7} as described in Table 4.¹⁴ We therefore compare the proportions of winners across draws within the subset of ranks {1, 3, 5, 7} where the variable of interest is the number of prime numbers that appear in the main draw.

We then extend the analysis to the bonus number. Under the null hypothesis that prime numbers are not more popular than composite numbers (non-prime numbers), there should be no difference between draws where the bonus number is prime and draws where it is not.

The following subsections describe how we construct the three separate popularity measures: one for the main draw and two for the bonus number draw.

2.4.1 | Measure of Popularity for the Numbers in the Main Draw

To evaluate the popularity of the numbers in the main draw, that is, excluding the bonus number, we calculate the proportion of winners over the set of ranks $R = \{1, 3, 5, 7\}$. The underlying idea is that when one (or several) popular number(s) appears in a draw, the proportion of winners over the ranks R deviates from the theoretical probability of winning under random selection, which is equal to $2.2037\% = 1.2277 \times 10^{-7} + 2.7992 \times 10^{-5} + 1.2946 \times 10^{-3} + 2.0714 \times 10^{-2}$, as shown in the last column of Table 4.

Our estimate of the popularity of a given number a is simply the average proportion of winners over R for the set of draws in which $a = 1, 2, \dots, 45$ appears. For a given draw i , we measure the popularity of the main draw by the percentage of winners (denoted PW) over $R = \{1, 3, 5, 7\}$. Formally, the *Proportion of Winners* (PW) is defined as

$$PW(i) = \frac{W_i(R)}{G_i}, \quad (2)$$

where G_i is the number of tickets sold at draw i and $W_i(R)$ is the cumulated number of winners at draw i over the ranks $R = \{1, 3, 5, 7\}$.

TABLE 4 | Number of winners per rank.

	Mean	Median	Standard deviation	Minimum	Maximum
Rank 1 (6+0)	0.44	0.00	0.73	0	5
Rank 2 (5+1)	2.48	2.00	2.40	0	21
Rank 3 (5+0)	97.80	86.00	51.63	22	507
Rank 4 (4+1)	245.18	222.00	120.35	75	1083
Rank 5 (4+0)	4544.38	4222.00	1885.43	1603	13187
Rank 6 (3+1)	6072.00	5678.50	2483.81	2216	17314
Rank 7 (3+0)	72904.98	70620.50	26853.98	30188	157363
Rank 8 (2+1)	54655.67	51497.50	20490.62	23264	137380
Rank 9 (1+1)	177222.88	173500.00	56062.02	91991	345694

Note: Columns 1 to 5 report statistics on the number of winners per rank. The total number of combinations is 8,145,060. Over our sample period, there was an important modification: A ninth rank of gain was introduced on May 26, 2018. This ninth rank (1 correct number plus the bonus number) pays a fixed amount equal to the ticket price, which is currently €1.25 (€1 before May 26, 2018).

The *Average Proportion of Winners (APW)* for a given number $a = 1, 2, \dots, 45$, calculated across all draws, is then defined by

$$APW(a) = \frac{1}{\#\Theta(a)} \sum_{i \in \Theta(a)} PW(i), \quad (3)$$

where $\Theta(a)$ is the set of draws in which the number a appears and $\#\Theta(a)$ is the cardinal of $\Theta(a)$, that is, the number of draws in which a appears.

2.4.2 | Measure of Popularity Based on the Bonus Number and Conditional Probabilities

Both sets of ranks $\{2, 4, 6\}$ and $\{3, 5, 7\}$ correspond to 5, 4, and 3 correct numbers in the main draw (see Table 4). The only difference between these two subsets of ranks is whether the bonus number is correct or not. Given the theoretical probabilities in the last column of Table 4, the expected proportion of winners with and without the bonus number is easy to compute.

Let us illustrate our approach with the example of ranks 4 and 5, which both correspond to four correct numbers in the main draw. At rank 4, the bonus number is correct while it is not at rank 5. Assuming players randomly pick their numbers, the probability of getting the bonus number correct, given that four numbers are correct in the main draw, is equal to

$$\frac{Pr(R_4)}{Pr(R_4) + Pr(R_5)} = \frac{7.00 \times 10^{-5}}{7.00 \times 10^{-5} + 1.29 \times 10^{-3}} = 5.15\%, \quad (4)$$

with $Pr(R_k)$ being the probability of winning at rank k .

Thus, among the winners with four correct numbers, we expect that 5.15% will also have the correct bonus number. If the bonus number is popular (unpopular) and played by a lot of (few) people, we expect the calculated percentage to be significantly higher (lower) than 5.15%.

To generalize this approach, we define below the notations and the process that define a measure of popularity for a bonus

number a . The reasoning developed in the preceding paragraph is aggregated over the set of ranks $\{2, 4, 6\}$. We sum the number of winners with, respectively, 5, 4, and 3 correct numbers in the main draw and the correct bonus number and we divide by the total number of winners with 5, 4, and 3 correct numbers (i.e., the cumulated number of winners over ranks 2 to 7). Denote $R = \{2, 3, 4, 5, 6, 7\}$ the set of ranks with 3 to 5 correct numbers and $R_b = \{2, 4, 6\}$ the set of ranks with 3 to 5 correct numbers and the correct bonus number. Also, denote $W_i(R)$ the cumulated number of winners over ranks in R at draw i and $W_i(R_b)$ the cumulated number of winners over ranks in R_b at draw i . The *Bonus Ratio (BR1)* at draw i is equal to

$$BR1(i) = W_i(R_b)/W_i(R), \quad (5)$$

and the *Average Bonus Ratio (ABR1)* over all draws for a given number a is defined as

$$ABR1(a) = \frac{1}{\#\Theta(a)} \sum_{i \in \Theta(a)} BR1(i), \quad (6)$$

where $\Theta(a)$ is the set of draws in which a appears as the bonus number. For a given draw i in which the bonus number a is popular (unpopular), $BR1(i)$ is expected to be significantly above (below) the expected value, which is equal to $Pr(R_b)/Pr(R)$.

2.4.3 | Measure of Popularity Based on the Bonus Number in Winning Ranks 8 and 9

As shown in Table 1, ranks 8 and 9 are two ranks that require the bonus number to be correct but also impose minimal conditions on the main draw (two correct numbers for rank 8 and one correct number for rank 9). We did not include these ranks in the definition of $BR1$ because there are no corresponding ranks without the bonus number. However, the aggregate probability of winning in the ranks $\{8, 9\}$ is approximately 7% (Table 1), which results in an average number of winners exceeding 230,000. We therefore introduce a new measure of popularity, which incorporates this information, to complete our estimation of the popularity of numbers. As mentioned before, the ninth rank

was introduced on May 26, 2018 (draw 460 in our sample). We therefore base the estimator on rank 8 before this date and on the pair of ranks {8, 9} after. Using the same notations as before, we define $BR2$, the second bonus ratio for a given number a and a given draw i as

$$BR2(i) = \frac{W_i(\{8\})}{G_i} \frac{1}{Pr(\{8\})}, \text{ if } i \leq 459, \quad (7)$$

$$BR2(i) = \frac{W_i(\{8, 9\})}{G_i} \frac{1}{Pr(\{8, 9\})}, \text{ if } i \geq 460, \quad (8)$$

and the *Average Bonus Ratio* ($ABR2$) for a number a is given by

$$ABR2(a) = \frac{1}{\#\Theta(a)} \sum_{i \in \Theta(a)} BR2(i), \quad (9)$$

where $\Theta(a)$ is the set of draws in which a appears as the bonus number. For a given draw i in which the bonus number a is popular (unpopular), $BR2(i)$ is expected to be significantly above (below) its expected value, which is equal to 1 under random choice. In the above definition of $ABR2$, the division by the theoretical probability ensures the comparability over the complete period.

3 | Empirical Analysis

3.1 | Univariate Analysis

We first provide univariate evidence that lotto players tend to bet more on prime numbers, compared to what is expected under random choice. Figure 2 presents a bar chart with the estimated popularity of each number from 1 to 45. Panel A provides the *Average Proportion of Winners* (APW) for the 45 numbers in the main draw, while Panels B and C refer to the *Average Bonus Ratios* ($ABR1$ and $ABR2$). We first see that the three graphs look very similar, a visual impression confirmed by correlations in the range [0.9730; 0.9927] between the three vectors APW , $ABR1$, and $ABR2$.¹⁵ We also observe, as mentioned above, that numbers less than or equal to 30 are more popular as a result of the birthday number effect. The three graphs also suggest that, on average, prime numbers are more popular than their immediate neighbors. The hypothesis that prime numbers are more popular, however, needs to be confirmed by a more thorough analysis.

In Panel A of Table 5, we look at the distribution of the *Proportion of Winners* (PW) of the different draws as a function of the number of primes in a draw. Over the 1044 draws of the sample, the mean PW for ranks {1, 3, 5, 7} is 2.1982%. This figure is close to the theoretical proportion of winners, which is equal to 2.2037%. However, PW ranges from a minimum of 1.4505% to a maximum of 3.3691%, showing a large heterogeneity of popularity with respect to the numbers that are drawn. The average proportion of winners is an increasing function of the number of primes in the draw which ranges from 2.1435% when there is no prime number in the draw to 2.3878% when there are five primes. Given that the average number of primes under random choice is $(14/45) \times 6 = 1.866$, the difference between the average proportion of winners when there are strictly less than two primes (2.1432%), compared

to draws with strictly more than two primes (2.2831%), is highly significant ($t = 5.8800$, $p = 0.0000$). We also compute, in the last column of Table 5 the difference between the observed PW and the theoretical value for draws with fewer than two primes, exactly two primes and more than two primes. We see that for the first category, that is, less than two primes, the observed PW is significantly below the theoretical value with a difference of -0.0605 . As expected, the t -test indicates an insignificant difference for the draws that contain exactly two primes. On the contrary, the PW for draws with more than two primes is positive (0.0794) and highly significant.

The univariate analysis of average bonus ratios is summarized in Panels B and C of Table 5. Regarding the first bonus ratio ($BR1$), the expected value is calculated from Table 1. $E(BR1) = 7.5393\%$, obtained by dividing the cumulated probability of ranks {2, 4, 6} by the cumulated probability of ranks 2 to 7. In short, the observed average of 7.5420% is not different from the expectation ($t = 0.0728$, $p = 0.9420$) on the entire sample of 1044 draws. However, from one draw to another, important differences appear in $BR1$ with a minimum (maximum) equal to 4.5378% (12.4396%). The comparison of $BR1$ in the two subsets of draws with and without a prime bonus number leads to an interesting result. In draws where the bonus number is not prime (respectively, prime), the average $BR1$ is 7.4215% (7.8207%), which is significantly lower (higher) than the theoretical value of 7.5393% (respectively, $p = 0.004$ and $p = 0.002$). Of course, the averages on the two subsamples are also significantly different from one another ($t = 5.0757$, $p = 0.0000$, statistics not reported in the table). For $BR2$, we know that the expected value is 1 but the values of $BR2$ vary from 0.6324 to 1.6287 over the 1044 draws. The averages of $BR2$ in the two subsets of draws with and without a prime bonus number are, respectively, 1.0350 and 0.9834. These values are significantly different from 1, the expected value of $BR2$ under random choice (Panel C of Table 5). Moreover, the averages of $BR2$ on the two subsamples are significantly different ($t = 5.7041$, $p = 0.0000$).

3.2 | Multivariate Tests

To demonstrate that prime numbers are more popular than non-prime numbers, we need to take into account several potential confounding factors.

There is substantial literature on conscious selection that provides explanations regarding the differences in the proportion of winners as a function of drawn numbers (e.g., Papachristou and Karamanis 1998; Roger and Broihanne 2007; Roger et al. 2023). The first factor we need to control for is the propensity of players to bet on birthday dates, which results in numbers less than or equal to 30 being overly selected. This tendency can be observed in our data, as shown in Figure 2. Controlling for this factor is important because it is likely to impact our results. Indeed, prime numbers are not uniformly distributed among the first 45 numbers. Over the interval [1;45], there is a slight over-representation of prime numbers in the first half of the interval (8 prime numbers), compared to the second half of the interval (6 prime numbers). As a result, selecting smaller numbers slightly, and mechanically, increases the propensity to play prime numbers. To account for such a confounding effect, we use the count of numbers below 30 in the draw as a control

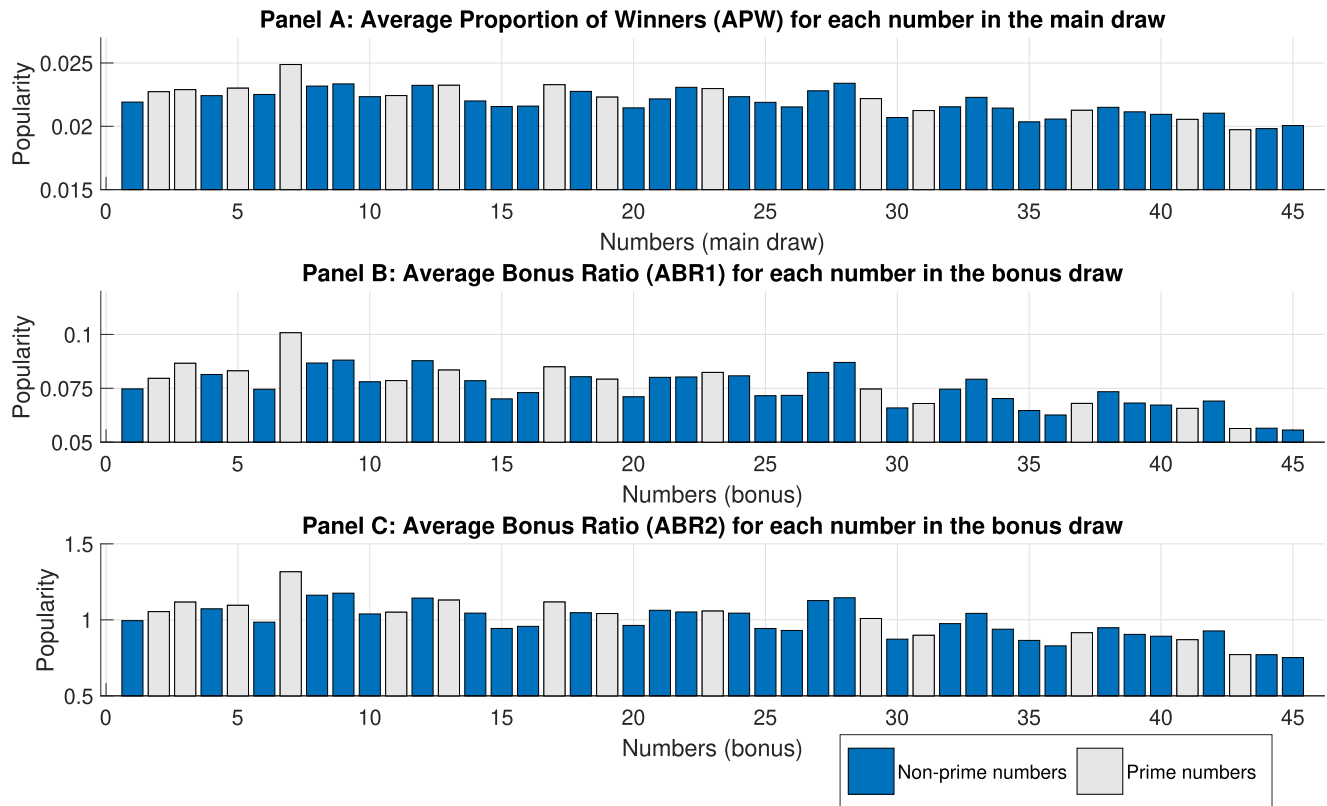


FIGURE 2 | Number popularity—APW, ABR1, and ABR2. *Note:* This figure provides the popularity of each number between 1 and 45. In Panel a, which corresponds to the main draw, the popularity is determined by the *Average Proportion of Winners (APW)*. In Panel b, which corresponds to the bonus draw, the popularity is assessed thanks to the *Average Bonus Ratio (ABR1)*. In Panel c, we report the alternative measure of bonus ratio ABR2. Prime numbers appear in gray while non-prime numbers appear in blue.
[Colour figure can be viewed at wileyonlinelibrary.com]

variable.¹⁶ We also take into account the fact that all primes except the number 2 are odds. Thus, a preference for prime numbers might simply reflect a preference for odd numbers. To control for this potential confounding effect, we use, for each draw, the count of non-prime odd numbers in the draw.

We also control for the lucky number effect, that is, the tendency to overplay the number 7, by introducing a dummy variable equal to 1 if the number 7 appears in the draw and 0 otherwise. Indeed, while 7 is a prime number, one could argue that people bet on number 7 because it is perceived as a lucky number, not because it is a prime number. In addition to controlling for the specificity of the numbers in the draws, we also consider whether the draw takes place on Wednesday or Saturday (there are two draws per week in the Belgian Lotto). The Saturday draws attract more players, and people tend to buy more tickets than they do on Wednesday draws. The average number of players is 452,129 on Wednesdays compared to 738,557 on Saturdays. Similarly, the average number of tickets per player increases from 5.44 on Wednesdays to 6.18 on Saturdays. If players fill out multiple tickets, their number selections on subsequent tickets may not follow the same pattern as on the first. D'Hondt et al. (2024) show that second tickets are closer to a random choice than first tickets. In particular, people who bet on their birthday dates on the first ticket have a tendency to select different numbers on the second ticket. Introducing a dummy variable enables us to account for the potential heterogeneity between individuals who

play on Wednesdays and those who play on Saturdays, as well as to control for any corresponding differences in their behavior.

We run the following regression:

$$\begin{aligned} Proportionofwinners_i = & \alpha + \beta_1 \#Primenumbers_i \\ & + \beta_2 \#Numbers \leq 30_i + \beta_3 Number7_i \\ & + \beta_4 \#Non - primeoddnumbers_i \\ & + \beta_5 \#Ticketsperplayer_i \\ & + \beta_6 Wednesdaydummy_i + \epsilon_i, \quad (10) \end{aligned}$$

where $Proportionofwinners_i$ is the proportion of winners at draw i . The proportion of winners is calculated using ranks 1, 3, 5, and 7. All these ranks correspond to ranks without bonus. $\#Primenumbers_i$ is the number of prime numbers in draw i , $\#Numbers \leq 30_i$ is equal, for draw i , to the number of drawn numbers that are less than or equal to 30, $Number7_i$ is a dummy variable equal to one if the number 7 appears in the main draw at draw i and 0 otherwise, $\#Non - primeoddnumbers_i$ is the number of non-prime odd numbers at draw i , $\#Ticketsperplayer_i$ is the average number of tickets per player at draw i , and $Wednesdaydummy_i$ is a dummy variable that is equal to 1 for the midweek draw and 0 otherwise.

TABLE 5 | Proportion of winners, bonus ratio and distribution of prime numbers.

Panel A: <i>PW</i> with respect to the distribution of prime numbers in the main draw						
Number of primes	Number of observations	Proportion of winners (in %)				Difference with theoretical <i>PW</i>
		Mean	Standard deviation	Minimum	Maximum	
0	100	2.1435	0.2836	1.4879	2.9550	−0.0605***
1	323	2.1431	0.2769	1.5301	3.1220	
2	361	2.2015	0.3033	1.4505	3.2053	−0.0021
3	190	2.2632	0.3147	1.5305	3.3691	
4	63	2.3314	0.3973	1.5378	3.3620	0.0794***
5	7	2.3878	0.2625	2.0754	2.8572	
All draws	1044	2.1982	0.3068	1.4505	3.3691	−0.0055

Panel B: <i>BR1</i> with respect to whether the bonus is a prime number						
Bonus is prime	Number of observations	Bonus ratio 1 (in %)				Difference with theoretical <i>BR</i>
		Mean	Standard deviation	Minimum	Maximum	
No	729	7.4215	1.0988	4.5378	11.2992	−0.1178***
Yes	315	7.8207	1.3097	4.5431	12.4396	0.2814***
All draws	1044	7.5420	1.1802	4.5378	12.4396	0.0026

Panel C: <i>BR2</i> with respect to whether the bonus is a prime number						
Bonus is prime	Number of observations	Bonus ratio 2				Difference with theoretical <i>BR</i>
		Mean	Standard deviation	Minimum	Maximum	
No	729	0.9834	0.1243	0.6503	1.4446	−0.0166***
Yes	315	1.0350	0.1553	0.6324	1.6287	0.0351***
All draws	1044	0.9990	0.1364	0.6324	1.6287	−0.0010

Note: Panel A provides statistics on the *Proportion of Winners (PW)* in the different draws with respect to the number of primes in the draw. Panel B and C report similar statistics about the *Bonus Ratios (BR1 and BR2)*, discriminating between draws where the bonus is a prime number and draws where it is not. The last column of Panels A to C gives the difference between the observed means and the theoretical one (for *BR2*, the theoretical mean is 1 by construction). Statistical significance of the difference is assessed with a *t*-test. In Panel A, the second column contains the number of draws with *k* prime numbers where *k* varies between 0 and 5. In Panels B and C, the second column indicates the number of draws where the bonus number was prime (respectively, non-prime). The third column gives, in Panel A, the average *Proportion of Winners (PW)* for the set of draws with *k* prime numbers and, in Panel B and C, the average bonus ratio (*ABR1* and *ABR2*) with respect to whether the bonus is a prime number or not. The next three columns contain the standard deviation, the minimum and the maximum in the corresponding category.

***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

We also look at the influence of the bonus being a prime number on the *Bonus Ratio*—either measured using *BR1* or *BR2*. We consider a regression model similar to the one defined above for the numbers in the main draw. We have:

$$\begin{aligned}
 \text{Bonusratio}_i = & \alpha + \beta_1 \text{Primebonus}_i + \beta_2 \text{Bonus} \leq 30_i + \beta_3 \text{Bonusequalto7}_i \\
 & + \beta_4 \text{Non-primeoddbonus}_i + \beta_5 \text{\#Ticketsperplayer}_i \\
 & + \beta_6 \text{Wednesdaydummy}_i + \epsilon_i,
 \end{aligned} \quad (11)$$

where *Primebonus_i* equals 1 if the bonus number is prime, and 0 otherwise, *Bonus* ≤ 30_{*i*} equals 1 if the bonus number is lower or equal to 30, and 0 otherwise, *Bonusequalto7_i* equals 1 if the bonus number is equal to 7, and 0 otherwise, and *Non-primeoddbonus_i* is equal to 1 if the bonus number is odd but not prime, and 0 otherwise.

Table 6 summarizes the results of the regressions. Column 2 provides the results of the model where the dependent variable is the *Proportion of Winners (PW)*. In Column 3 (4), the dependent variable is the bonus ratio *BR1* (*BR2*). Despite the different

TABLE 6 | Multivariate analysis.

	<i>Proportion of winners (PW)</i>	<i>Bonus Ratio (BR1)</i>	<i>Bonus Ratio (BR2)</i>
Number of prime numbers	0.0002*** (3.16)		
# Numbers ≤ 30	0.0017*** (27.11)		
Number 7 (Main draw)	0.0026*** (11.86)		
# Non-prime odd numbers	−0.0000 (−0.45)		
Prime bonus		0.0017*** (2.62)	0.0263*** (3.75)
Bonus ≤ 30		0.0123*** (20.05)	0.1571*** (24.24)
Bonus equal to 7		0.0205*** (9.22)	0.2543*** (10.65)
Non-prime odd bonus		−0.0010 (−1.31)	−0.0037 (−0.43)
# Tickets per player	−0.0003* (−1.76)	0.0010 (1.41)	0.0117 (1.50)
Wednesday dummy	−0.0002 (−1.31)	0.0012 (1.55)	0.0107 (1.32)
Intercept	0.0161*** (16.39)	0.0600*** (14.07)	0.8050*** (17.02)
Number of observations	1044	1044	1044
R2	0.531	0.367	0.438

Note: This table presents the results of three regression models. The first model concerns the numbers in the main draw and the two others the bonus. For the first model, *PW* is regressed (1) on the number of primes in the official draw which is the independent variable of interest, (2) on the number of numbers less than or equal to 30 to control for the birthday number effect, (3) on the dummy equal to 1 if 7 shows up in the main draw to control for the lucky number effect, (4) on the number of odd numbers that are not prime to distinguish the prime number effect from a potential odd number effect, (5) on the average number of tickets per player to control for the sequential choice effect described in D'Hondt et al. (2024), and (6) on the day of the week to control for the heterogeneity of players across midweek or week-end draws (equal to 1 if the draw takes place on a Wednesday). The two other models are defined equivalently with the bonus ratio (*BR1* or *BR2*) as the dependent variable. The independent variable of interest is a dummy identifying the bonus number as prime or not prime. The control variables are a direct transposition to the bonus number of the set of control variables in the first model. *t*-statistics are in parentheses.

***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively, using robust standard errors.

controls, we find that the number of prime numbers in the main draw is significantly and positively linked to the proportion of winners ($t = 3.16$, $p = 0.002$). As expected, the regression coefficient for the variable Numbers ≤ 30 is positive and highly significant ($t = 27.11$, $p = 0.0000$). The strength of the effect is in line with well-known results in the literature (Papachristou and Karamanis 1998; Roger and Broihanne 2007; Turner 2010; Polin et al. 2021; Roger et al. 2023). We also find, as expected, that the Number 7 dummy is highly significant ($t = 11.86$, $p = 0.0000$). Neither the count of non-prime odd numbers nor the day of the week influences the proportion of winners at ranks 1, 3, 5, and 7.

In Columns 3 and 4, we check if the *Bonus Ratios* (*BR1* and *BR2*) depend on whether the bonus is prime. We find a positive

and highly significant coefficient for the variable *Prime bonus* ($t = 2.62$, $p = 0.0090$ for *BR1* and $t = 3.75$, $p = 0.0000$ for *BR2*). Here again, we control for the tendency to play smaller numbers by introducing a dummy variable equal to 1 if the bonus is less than or equal to 30, and 0 otherwise. This variable is highly significant in the two regressions ($t = 20.05$, $p = 0.0000$ for *BR1* and $t = 24.24$, $p = 0.0000$ for *BR2*). We also control for the lucky number effect by introducing a dummy variable that takes the value 1 if the bonus is 7 and 0 otherwise. This variable is also quite significant ($t = 9.22$, $p = 0.0000$ for *BR1* and $t = 10.65$, $p = 0.0000$ for *BR2*). Finally, we observe that whether the bonus number is a non-prime odd number does not influence the bonus ratio.

TABLE 7 | Gains with respect to number of primes.

Panel A: Average gains (in euros)						
Number of primes	0	1	2	3	4	5
Rank 6	10.66	10.52	10.44	10.22	9.88	8.34
Rank 5	27.03	27.07	26.39	25.28	24.22	22.47
Rank 4	279.58	279.09	277.90	268.42	256.24	204.04
Rank 3	1538.54	1582.11	1559.38	1491.45	1376.14	1066.59
Panel B: Differences in gains (in euros and %)						
Categories	0 vs. 12345	01 vs. 2345	012 vs. 345	0123 vs. 45	01234 vs. 5	01 vs. 345
Rank 6	0.28 (2.66%)	0.26** (2.47%)	0.41*** (3.93%)	0.72** (6.92%)	2.07*** (20.02%)	0.47*** (4.41%)
Rank 5	0.80 (2.96%)	1.27*** (4.70%)	1.80*** (6.72%)	2.42*** (9.14%)	3.86* (14.83%)	2.11*** (7.80%)
Rank 4	5.17 (1.85%)	7.24* (2.59%)	14.87** (5.33%)	25.60** (9.27%)	71.34*** (26.20%)	15.47*** (5.54%)
Rank 3	0.94 (0.06%)	57.36** (3.68%)	114.02*** (7.31%)	206.34*** (13.37%)	474.29** (31.42%)	119.74*** (7.67%)

Note: Panel A shows the average gain for ranks 3, 4, 5, and 6 conditional on the number of prime numbers in the main draw. Panel B displays differences in average gains across categories defined by the number of prime numbers in the draws. The percentage difference between two categories x and y is computed as the difference in their average gains divided by the average gain in category x . The last column reports the difference between draws with fewer than two primes, which is the expected number of primes per draw, and draws with more than two primes.

***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

3.3 | Economic Implications

Beyond the statistical relationship established above, we need to assess the economic implications of the popularity of prime numbers for lotto players. Under the parimutuel principle, which the Belgian Lotto obeys, the more winners there are, the lower individual gains are. Therefore, the important question is: How much does one lose when betting heavily on prime numbers? To answer this question, we examine the time series of gains at the different ranks and discriminate based on the number of primes in the draw. Table 7 shows the average gains at ranks 3 to 6 with respect to the number of primes in the draw. We focus on ranks 3 to 6 because (1) the gain is a fixed amount for ranks 7 to 9 and (2) there are a number of draws without winners at ranks 1 and 2. Overall, we find a (quasi) monotonic and negative relationship between the number of primes in the draw and the average gains. For instance, for rank 4, the average gain when there is 0 prime number in the draw is approximately €280 while it is only about €204 when there are five prime numbers. Panel B provides information regarding the statistical significance of these differences. We group gains in categories (with respect to the number of primes in the draws) and compare the gain for each pair of categories (0 vs. more than 0, 0 and 1 vs. more than 1, ...). Overall, we find that the difference in gains between the different categories is statistically significant (except for the case of 0 prime vs. more than 0 primes). It means that the more prime numbers there are in a draw, the lower the expected gain is. It follows that it is clearly suboptimal for players to choose prime numbers. Foregone gains can be substantial. For instance, selecting five prime numbers leads

to gains that are 14.83% to 31.42% lower than when selecting fewer than five primes. The last column (in bold) provides the statistical significance of the difference between the gains when there are strictly fewer than 2 primes in the draw and the gains when there are strictly more than 2 primes. In this specification, we exclude draws with exactly two primes because this case corresponds approximately to the expected number of primes under random choice (which is equal to 1.8666). Thus, this last column compares the situations where there are, on the one hand, less primes than expected in a random choice and, on the other hand, more primes than expected. The differences are highly significant.

4 | Results Using Alternative Data

In this section, we compare the popularity of the numbers from 1 to 45 in our sample, as measured by APW , $ABR1$ and $ABR2$, to the popularity of these same numbers in alternative samples. We use data from two different papers (Roger et al. 2023; D'Hondt et al. 2024). For these data, the popularity of the numbers is simply given by the frequency at which they were chosen by the players. To ensure compatibility, we standardize the different measures of popularity. We thus have:

$$PM^{st}(a) = \frac{PM(a) - E(PM)}{\sigma_{PM}}, \quad (12)$$

where PM is a given popularity measure (APW , $ABR1$, $ABR2$, or the frequency).

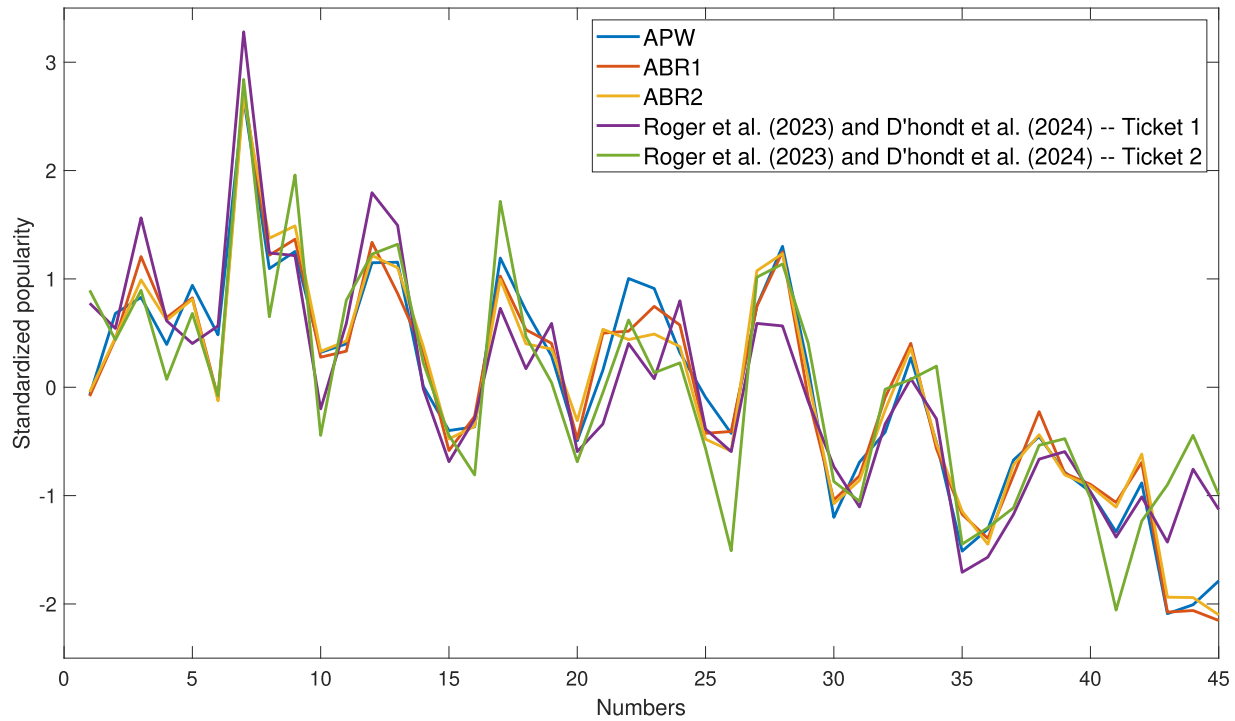


FIGURE 3 | Standardized popularity across data sets. *Note:* To ensure compatibility between the different measures of popularity, we standardize the five measures as follows: $PM^{st}(a) = \frac{PM(a) - E(PM)}{\sigma_{PM}}$, where PM is a given popularity measure (APW , $ABR1$, $ABR2$, or the frequency). [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 8 | Correlations between popularity measures from different data sets.

	Current article			Roger et al. (2023) and D'Hondt et al. (2024)	
	<i>APW</i>	<i>ABR1</i>	<i>ABR2</i>	Frequency (ticket 1)	Frequency (ticket 2)
<i>APW</i>	1				
<i>ABR1</i>	0.9752	1			
<i>ABR2</i>	0.9730	0.9927	1		
Frequency (ticket 1)	0.8975	0.8965	0.8988	1	
Roger et al. (2023); D'Hondt et al. (2024)					
Frequency (ticket 2)	0.8623	0.8424	0.8631	0.9097	1
Roger et al. (2023); D'Hondt et al. (2024)					

Note: This table provides the correlations between the different measures of popularity. All the correlation coefficients are significant at the 1% level.

Figure 3 reports the five standardized popularity measures. The different data sets have strong common features, the two most notable being the specific role of number 7 and the birthday number effect, which leads to a larger popularity of numbers lower than 30, compared to numbers greater than 30. This similarity between the data sets is further confirmed by the correlation matrix in Table 8. The correlations between the standardized popularity measures range from 0.8424 to 0.9927.

As mentioned previously, our alternative data sets come from Roger et al. (2023) and D'Hondt et al. (2024). In each of the two studies, a survey was conducted where respondents had to fill out two tickets of a 6/45 lotto game. Aggregating the two data sets (489 and 498 respondents, respectively) gives us a total of 987 pairs

of tickets. We consider separately the first and the second ticket since D'Hondt et al. (2024) show that in sequential choices, people select numbers differently on the second ticket. As a consequence of respondents spending less time selecting numbers for the second ticket, conscious selection appears weaker and the tickets are somewhat closer to what could be expected under random choice. We look at the number of prime numbers in each ticket in order to show whether individuals exhibit a preference for prime numbers. The results are summarized in Table 9.

For ticket 1 (2), there is on average 2.04 (2.01) prime numbers per ticket, when the expected number under random choice is

TABLE 9 | Data from Roger et al. (2023) and D'Hondt et al. (2024).

Panel A: Data from ticket 1					
Number of primes	Theoretical	Average	Minimum	Maximum	Difference from theoretical value
Number of prime numbers	1.87	2.04	0	6	0.17***
Number of prime numbers (without 7)	1.77	1.86	0	6	0.09**
Panel B: Data from ticket 2					
Number of primes	Theoretical	Average	Minimum	Maximum	Difference from theoretical value
Number of prime numbers	1.87	2.01	0	6	0.14***
Number of prime numbers (without 7)	1.77	1.84	0	6	0.07**

Note: This table provide statistics regarding the number of prime numbers in each ticket in the data provided by Roger et al. (2023) and D'Hondt et al. (2024). When number 7 is excluded, the number of prime numbers is adjusted according to Equation (13). The statistic significance of the difference in the last column is assessed with a *t*-test.

***, **, and * indicate statistical significance at the 1%, 5%, and 10%.

$1.87 = 6 \times 14/45$. The difference between the observed number of prime numbers and the theoretical one is highly significant. For ticket 1, we have $t = 4.8567$ and $p = 0.0000$. The corresponding figures are $t = 3.6691$ and $p = 0.0000$ for ticket 2. We also consider the possibility that our results are driven by individuals overly selecting number 7 as a result of it being a lucky number (instead of a prime number). To account for the impact of number 7, we proceed as follows. For tickets that contain number 7, we are left with a selection of 5 numbers among 44. Under a random choice assumption, the expected number of primes (of course different from 7) among these five numbers is $13 \times 5/44$, that is, 1.4773. To aggregate tickets that contain number 7 and tickets that do not, we simply rescale the number of prime numbers for tickets containing number 7 as follows. If $N_{prime}(7)$ is the number of prime numbers played by people who select number 7 on their ticket, we rescale this number in

$$(N_{prime}(7) - 1) \times \frac{6}{5}. \quad (13)$$

Overall, the findings are similar for ticket 1 and ticket 2. When excluding number 7, the difference with the theoretical value decreases slightly, to 0.09 for ticket 1 and 0.07 for ticket 2, but remains significant at the 5% level.

5 | Additional Analyses

In this section, we provide evidence that the higher selection of prime numbers is not incidental but reflects, at least in part, an awareness of the arithmetical properties (primality) of the numbers chosen. To do so, we conduct two additional analyses. First, using survey data from D'Hondt et al. (2024), we show that numeracy is the only player characteristic that significantly predicts the overselection of prime numbers. Second, we show that our results are not driven by a simple selection rule such as the avoidance of certain composite numbers (e.g., multiples of 2, multiples of 3, or multiples of 5).

5.1 | The Role of Numeracy

The data from D'Hondt et al. (2024) provide a suitable setting to assess whether the overselection of prime numbers

reflects their mathematical properties or instead arises from non-mathematical selection rules. The richness of the data set allows us to relate number choices to individual characteristics, including a direct measure of numeracy and several proxies for common number-selection heuristics.

Our empirical strategy tests whether the association between numeracy and prime selection persists once we account for alternative motives that are unrelated to the mathematical nature of primes. In particular, we examine the relation between numeracy and the propensity to select prime numbers while controlling for the propensity to choose lucky numbers, birthdays, and age-related numbers. These controls capture salient and well-documented heuristics in lottery number choice and therefore provide a natural benchmark for non-mathematical selection mechanisms.

If prime numbers are selected because of their mathematical properties, their selection should be positively associated with numeracy even conditional on these heuristic-based propensities. Conversely, if prime selection primarily reflects salience or familiarity, this association should weaken once these channels are accounted for.

Panel A of Table 10 reports descriptive evidence on the relation between numeracy and prime selection. Numeracy is measured using three questions adapted from the Berlin Numeracy Test (Cokely et al. 2012).¹⁷ The mean number of selected primes increases monotonically with numeracy. Respondents with low numeracy (zero or one correct answer) select fewer prime numbers than those with higher numeracy, suggesting a positive raw association between numerical ability and prime selection.

Panel B reports OLS estimates of this relation. In Model 1, numeracy is positively associated with the number of primes selected: A one-point increase in the numeracy score is associated with an increase of 0.135 primes (statistically significant at the 5% level). Model 2 introduces demographic controls and measures of heuristic-based number selection. The coefficient on numeracy remains virtually unchanged in magnitude and significance. The stability of this coefficient indicates that the relation between numeracy and prime selection is not driven by observable

TABLE 10 | Numeracy and the selection of primes numbers.

Panel A: Average number of primes and numeracy score		
Numeracy score	Number of respondents	Number of primes
0	21	1.62
1	90	1.90
2	191	2.15
3	196	2.15
Panel B: Regression of prime numbers on numeracy		
	Model 1	Model 2
Numeracy score	0.14** (2.19)	0.14** (2.11)
Female dummy		0.07 (0.62)
Age		0.00 (1.08)
Language		0.00 (0.02)
Log income		0.04 (0.38)
Propensity to play lucky numbers		0.02 (0.80)
Propensity to play birthdays		0.04 (1.48)
Propensity to play ages		−0.03 (−0.91)
Number of observations	498	497
R2	0.01	0.02

Note: Panel A reports the mean number of prime numbers selected on the first lotto ticket by numeracy score, using the survey data of D'Hondt et al. (2024). The numeracy score is based on three questions measuring the ability to work with percentages, proportions, and compound interest, and ranges from 0 (no correct answers) to 3 (all correct answers). Under random choice, the expected number of primes is $6 \times 14/45 = 1.867$. Panel B reports OLS estimates of the number of prime numbers selected on the first lotto ticket. Model 1 includes only the numeracy score. Model 2 adds demographic controls and measures of number-selection heuristics. The female indicator equals one for female respondents. Age is measured in years. Language is an indicator equal to one for French-speaking respondents (and zero for Dutch-speaking respondents). Log income is the natural logarithm of monthly household net income (in euros). Propensity to select lucky numbers, birthdays, and age-related numbers are measured on 7-point Likert scales capturing self-reported tendencies to rely on these heuristics when choosing lotto numbers. Robust standard errors are used. *t*-statistics are reported in parentheses. Results are qualitatively unchanged when estimating ordered response models (ordered logit).

***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

characteristics or by the propensity to rely on salient number-selection heuristics. Moreover, proxies for usual heuristics are not significant once numeracy is included in the regression.

Taken together, these findings show that individuals with higher numeracy are more likely to select prime numbers conditional on common non-mathematical selection rules. This pattern is consistent with the interpretation that primes are selected, at least in part, because of their mathematical properties rather than because they are incidentally associated with salient or personally meaningful numbers.

5.2 | Avoidance of Multiples

An alternative interpretation is that the overselection of prime numbers does not reflect any intrinsic salience of primality, but instead arises mechanically from players' tendency to avoid multiples of small integers. Indeed, over the $1, \dots, 45$ range, the sets of prime numbers and the set of non-multiples of 2, 3, and 5 are nearly identical. The only integer in this range that is neither prime nor a multiple of 2, 3, or 5 is 1. As a result, a heuristic that disfavors multiples of 2, 3, and 5 would mechanically generate an apparent preference for primes.

TABLE 11 | Proportion of winners and bonus ratios with respect to the distribution of multiples.

Panel A: <i>PW</i> with respect to the number of multiples						
	Multiples of 2		Multiples of 3		Multiples of 5	
	<i>N</i>	Diff.	<i>N</i>	Diff.	<i>N</i>	Diff.
0	11	0.1951	84	0.0041	258	0.1126***
1	97	0.0511	246	0.0019	448	−0.0014
2	242	0.0244	390	−0.0186	257	−0.0892***
3	365	−0.0440***	241	−0.0113	70	−0.1440***
4	240	−0.0086	67	0.0465	11	−0.1047
5	74	−0.0478	16	0.0220		
6	15	0.1970**				

Panel B: <i>BR1</i> with respect to whether the bonus is a multiple						
	Multiple of 2		Multiple of 3		Multiple of 5	
	<i>N</i>	Diff.	<i>N</i>	Diff.	<i>N</i>	Diff.
No	539	0.0196	685	0.0312	821	0.1750***
Yes	505	−0.0155	359	−0.0518	223	−0.6319***

Panel C: <i>BR2</i> with respect to whether the bonus is a multiple						
	Multiple of 2		Multiple of 3		Multiple of 5	
	<i>N</i>	Diff.	<i>N</i>	Diff.	<i>N</i>	Diff.
No	539	0.0042	685	0.0034	821	0.0201***
Yes	505	−0.0065	359	−0.0094	223	−0.0786***

Note: This table combines results for multiples of 2, 3, and 5. Panel A reports the *Proportion of Winners (PW)* by the count of multiples in the main draw. Panels B and C report *BR1* and *BR2* according to whether the bonus number is a multiple of 2, 3, or 5. “No” indicates the bonus is not a multiple of the relevant integer; “Yes” indicates it is. Diff. gives the difference between the observed mean and the theoretical value. For *BR2* the theoretical mean is 1 by construction.

***, **, and * indicate significance at the 1%, 5%, and 10% level (*t*-test).

We assess this alternative hypothesis by examining whether multiple avoidance predicts the proportion of winners and the bonus ratios. We consider separately multiples of 2, 3, and 5. Table 11 reports the results. Panel A shows the difference between the observed and theoretical proportion of winners (*PW*) as a function of the number of multiples of 2, 3, and 5 in the six main draw numbers. Panels B and C report analogous differences for the bonus ratios *BR1* and *BR2*, depending on whether the bonus number is a multiple of 2, 3, or 5.

In Panel A, the proportion of winners (*PW*) shows no systematic relationship with the number of multiples of 2 or 3. For multiples of 2, estimates vary in sign and are rarely statistically significant, with no monotonic pattern across categories. For multiples of 3, deviations are small and never statistically distinguishable from zero. These results indicate that the presence of such multiples in the main draw does not affect the proportion of winners (*PW*) in a meaningful way.

By contrast, multiples of 5 exhibit a clear pattern. As the number of multiples of 5 increases, the proportion of winners declines, with statistically significant negative deviations for intermediate counts (two and three multiples). Conversely, draws without multiples of 5 display a significant excess of winners.

Panels B and C yield the same conclusion for the bonus number. For multiples of 2 and 3, both *BR1* and *BR2* remain close to their theoretical benchmarks, with no statistically significant differences. In contrast, when the bonus is a multiple of 5, both ratios are significantly below their theoretical values, while the opposite holds when the bonus is not a multiple of 5.

Overall, the results indicate that the effect is confined to multiples of 5.¹⁸ For multiples of 2 and 3, estimates are small and statistically indistinguishable from zero across most panels. This pattern is informative for the interpretation of prime number overselection. If the overselection of primes was driven by a general avoidance of multiples, similar effects should appear for multiples of 2 and 3. Their absence weakens that explanation. Instead, the results suggest that players avoid numbers ending in 0 or 5, rather than multiples per se.

6 | Conclusion

Our study primarily uses Belgian data to investigate whether lotto players exhibit a preference for prime numbers. Specifically, we conduct statistical and econometric analyses on a sample of 1044 lotto draws from January 2014 to December 2023. To assess the popularity of prime numbers relative to other numbers, we develop measures of popularity of numbers based on the actual

proportion of winners across specific subsets of ranks. The main advantage of this methodology is that it enables us to identify variations in conscious selection across draws. Our results show that prime numbers are more popular than non-prime numbers. We demonstrate this preference in two ways. First, by examining the proportions of winners in ranks that exclude bonus numbers, we find that the number of prime numbers in a draw significantly influences the proportion of winners, even after controlling for the birthday number effect, the presence of the number 7 in the draw, the day of the week and the count of other odd numbers that are not prime. Second, we build two measures of popularity based solely on the bonus number, which yield similar results: a prime bonus number in the draw significantly affects the proportion of winners at ranks that include the bonus number. Finally, we show that playing prime numbers significantly impacts one's expected gains, conditional on winning. Our main result is further supported by survey data from two published studies, all of which reinforce the existence of a preference for prime numbers. While the results are highly robust, the data do not allow us to identify the psychological source of the preference for prime numbers. It may stem from the availability heuristic, as prime numbers are taught early in school, or from their more "random-looking" nature.

These findings have implications for the design and regulation of lottery games. Since Farrell et al. (2000), it has been established that players do not choose lottery numbers uniformly, and that this conscious selection affects the distribution of prize winners. Baker and McHale (2009) further show that conscious selection produces substantial overdispersion in the number of winners and strongly affects the moments of the ticket value distribution, in particular skewness, which are key inputs into the design of attractive new games. Our evidence that players overselect prime numbers contributes to this literature by identifying a specific and robust regularity in conscious selection. From the operator's perspective, this regularity affects the distribution of winners across prize tiers: Draws in which the winning combination is disproportionately composed of prime numbers produce more shared jackpots and lower per-winner payouts, which influences both the perceived attractiveness of the game and the variance of the operator's liabilities. From the regulator's perspective, the same regularity implies that the effective expected value of a ticket varies across combinations, so that informed players can raise their expected payoff, though not their probability of winning, by avoiding over-played numbers, a point made explicitly by Baker and McHale (2009). This asymmetry suggests a concern that is rarely discussed in lottery policy: Players who are aware of conscious selection patterns extract higher expected returns at the expense of players who are not, introducing a form of sophistication-based redistribution within a game that is nominally one of pure chance.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data sets analyzed in the article are either publicly available or available from the authors on reasonable request.

Endnotes

¹For instance, lottery players tend to overweight previously drawn numbers, a behavior known as the hot-hand fallacy (Gilovich et al. 1985). Conversely, they may also fall prey to the gambler's fallacy, causing them to favor numbers that have not appeared in official draws for an extended period (Clotfelter and Cook 1993; Lien and Yuan 2015; Ho et al. 2019; Polin and Benisaac 2023; Dillon and Lybbert 2024). These two behaviors can even coexist in some cases (Ayton and Fischer 2004; Suetens et al. 2016; Kong et al. 2020). See Perez and Humphreys (2013) for a review.

²The expression "conscious selection" seems to refer to conscious choices, but number preferences can sometimes be unconscious. For example, in criminal justice contexts, Dhami et al. (2020) find that judges exhibit preferences for specific numbers when assigning sentence durations or fines.

³Baker and McHale (2011) provide an example from the Canadian lottery draw on March 19, 2008, where the winning numbers were 23, 40, 41, 42, 44, and 45, with 43 as the bonus number. Although no one won the jackpot, an unusually high number of players (239) won second prize by matching five numbers plus the bonus. This example highlights the popularity of certain number sequences.

⁴It is, however, already difficult to rationalize the simple act of gambling on state lotteries given the substantial take-out rate (Stetzka and Winter 2023).

⁵The term "conscious selection" originates with Cook and Clotfelter (1993) and refers to any number selection process that leads to aggregate choices deviating from a uniform distribution. Subsequent work adopts a similar definition, interpreting it as non-random selection (e.g., Baker and McHale 2009; 2011; Stetzka and Winter 2023). While the term may suggest deliberate choice at the individual level, such an interpretation is not required. We retain this standard terminology, although alternative labels such as "manual selection" have been proposed (Polin et al. 2021).

⁶A publicly available data set from the Belgian National Lottery (<https://www.loterie-nationale.be/>)

⁷The Belgian population counts 11 million people.

⁸The two data sets were previously used in D'Hondt et al. (2024) and Roger et al. (2023), respectively, and were kindly shared by the authors.

⁹For centuries, prime numbers have fascinated mathematicians. Understanding their distribution remains a topic of interest since Euclid's proof (c. 300 BC) that there exists an infinity of prime numbers. As the fundamental building blocks of arithmetic, prime numbers have numerous practical applications, particularly in cryptography and computer science. Also, the search for the largest prime number, along with the broader effort to understand their distribution remains a focal point in mathematical research. Beyond mathematicians, prime numbers attract interest from non-specialists due to their distinctive mathematical properties and the intriguing questions they raise about the nature of numbers. Prime numbers have also captured the popular imagination, featuring in movies and television. Perhaps the most widely recognized instance is the so-called *Sheldon Conjecture* in the television series *The Big Bang Theory*, which centers on the number

73 (Byrnes et al. 2015; Pomerance and Spicer 2019). In a similar vein, the *Washington Post* (September 26, 2016) ran a story titled “The Magnificent Seven and 5 Other Movies with Prime Numbers in Their Titles.”

¹⁰ The Euromillions lottery is characterized by $(N, n, b) = (50, 5, 2)$ but a ticket consists of selecting five numbers for the main draw and two bonus numbers.

¹¹ Details can be found in the legal document (Arrêté royal, March 21, 2018) available at https://www.etaamb.be/fr/arrete-royal-du-01-avril-2016_n2016003257.html.

¹² <https://www.loterie-nationale.be/>.

¹³ We thank the authors for sharing their data.

¹⁴ Table 4 shows that the median number of winners for rank 1 (6 correct numbers) is 0, making it impossible to build a measure of popularity based uniquely on the proportions of jackpot winners.

¹⁵ See Table 8 for the details.

¹⁶ Using the count of numbers below 31 instead yields identical results.

¹⁷ The three questions are: (1) If the probability of catching a disease is 10%, how many people out of 1000 will catch it on average?; (2) If five people have matched all the winning Lotto numbers and the jackpot is two million euros, how much will each of them receive?; and (3) Suppose you have €200 in a savings account earning 10% interest per year. How much will you have in your account after 2 years?

¹⁸ The finding that players avoid numbers ending in 0 or 5 is consistent with an established literature on the perception of randomness in lottery number selection. Hardoon et al. (2001); Ladouceur et al. (1995), and Krawczyk and Rachubik (2019) show that players systematically prefer number combinations that look random over combinations with visible structure. Krawczyk and Rachubik (2019), in particular, use three distinctive sequences composed exclusively of numbers ending in 0 or 5, and find that 70% of subjects reject such sequences in favor of random-looking ones. Sevilla and Bagchi (2014) show that numeric roundness influences probability perceptions more broadly. In the range of the Belgian Lotto, multiples of 5 are the most visually salient numerical category: Their terminal digit makes them immediately recognizable.

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