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Rapid demand curves: Reward valuation using behavioral economics

Charles Nastos

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Rapid Demand Curves: Reward Valuation using Behavioral Economics

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JAMES MADISON UNIVERSITY

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Abstract

Within the past few decades, the psychological field of operant behaviorism has converged with the field of economics to aid in the description and interpretation of behavior. In doing so, more stringent, empirical methods of measuring and analyzing behavior have been produced. Laboratory experiments with both human and non-human animals have been used to study concepts that are integral to both fields, such as supply and demand, scarcity, and choice behavior. One goal of behavioral-economic research is to establish a demand function; that is, how does a change in the price of a commodity influence changes in its consumption? Consequently, what other factors influence consumption beyond changes in price alone? The current study aimed to replicate previous research and present further evidence for the generation of a demand function by observing the food consumption of animal subjects (pigeons) under controlled conditions. Specifically, an increasing fixed-ratio (FR) schedule of reinforcement was used over a short period of time (5 days) to rapidly measure changes in demand. Outcomes frequently related to responding in behavioral experiments (i.e., interresponse-times, post-reinforcement pauses, and shifts in weight) were also measured. A repeated measures ANOVA evidenced significant decreases in consumption as price increased. Behavioral economic formulae provided moderate to strong model fits for demand data (average $R^2 = 0.83$), suggesting that demand behavior is able to be measured under speeded conditions and across species.

Keywords: Behavioral Economics, Choice Behavior, Consumption, Demand, Closed vs. Open Economy, Schedule of Reinforcement

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Behavioral Economics

Behaviorism is an area of psychology devoted to understanding the science of behavior; specifically, how organisms operate in relation to their environment, and how these responses can be observed, analyzed, and explained (Baum, 2016). Prior to behaviorism's formation, psychology relied mostly on subjective interpretations of experiences, such as descriptions of sensations, perceptions, and emotions; the study of these accounts that stemmed from the "mind" came to be known as structuralism (Moore, 2011). Although these introspective methods of understanding human cognition (and in turn, behavior) were pertinent at the time, it was evident that relying on subjective reports could not provide objective conclusions about how humans function (Moore, 2011). Skeptics of these cognitive processes sought to bring the newly formed area of behavioral psychology into a league with that of "hard" sciences, such as biology or physics. Although his reputation and methods are controversial today (e.g., the aversive conditioning of "Little Albert" to white stimuli), John Watson was one of the early advocates for the push of psychological research towards outcomes that could be directly observed (Watson, 1913). In his writings, Watson argued that behaviorism is objective in its scientific foundations because of its direct measurability of behavior (not self-report), but simultaneously acknowledged that completely disregarding cognitive processes would be detrimental in holistically describing how organisms work. Although areas of psychology like cognition and neuroscience have risen in prevalence over time, the early strides made by behaviorists in developing empirical practices should not be overlooked. The ability to alter outcomes through the manipulation of external stimuli was essential

for the proponents of the experimental analysis of behavior and has been applied to many other areas of psychology as well (Moore, 2011).

Fortunately, another field of science, economics, was also dedicated to the study of what affects behavior. Economic research typically studies human behavior as microeconomics (studies of individuals and their decision-making processes) and macroeconomics (studies of the behavior of groups of people or even societies) (Coleman, 1984; Sianesi & Reenen, 2003). Subject areas in economics includes concepts such as scarcity, supply and demand relations, and consumer behavior. Like psychology, economics was focused on interpreting how organisms (mostly humans) distributed their available resources given the environmental stipulations presented (Mazur, 2016). For example, shifts in prices of goods like food, technology, or textiles could be examined by economists to understand how people, cultures, or even countries differentially valued those things. Likewise, behavioral psychologists could determine how much a single pellet of food was worth to a mouse by observing its willingness to work. It seemed that both behavioral psychology and economics were successfully studying behavior, but were they doing so efficiently? In other words, were both sciences considering many possible reasons for the outcomes they observed, or were they pigeon-holed by the constraints of their respective learnings? For instance, how different was the expenditure of an animal's time waiting for the opportunity to press a lever from a Wall Street banker carefully allocating her time to buy the cheapest stocks?

More recently (in the past few decades), researchers have specifically sought to incorporate economic concepts and behavioral principles to obtain a more complete understanding of behavior (Bradshaw, 2010). The convergence of these two facets

became known as behavioral economics. It is worth noting that this combination of ideologies was not a competition of who could explain what better, but a meeting of related philosophies with a similar goal of measuring behavior. Bickel, Green, and Vuchinich (1995) stressed the necessity of this integration with regards to the representation and analysis of everyday behavior, while also highlighting the important differences between the two disciplines. For example, one of their most salient points was made by first evidencing the growing number of research publications using behavioral economic terms over the last 50 years. Specifically, no mentions of behavioral-economic publications had appeared before 1974, but were seen upwards of 10 times by 1990. Bickel, Green, and Vuchinich's goal was not just to draw attention to these occurrences, but to highlight that scientists who had already been studying related behaviors in both fields were now borrowing verbiage, explanations, and formulae from each other more frequently. Hursh (1984) also presented his opinions about the value that could come from the addition of the two areas of study. He specifically aimed to discuss the worth that economic theory could provide to those studying behavior without downplaying its importance in its own right. For behavioral psychology, Hursh proposed that the use of economic principles was most relevant when it could be tested using experimental interventions and could provide convergent evidence across the sciences. These criteria are valuable in that they provide a more concrete basis for the mixture of behavior analysis and economics beyond just a shared nomenclature for similar concepts.

Although there were clear benefits to the union of behaviorism and economics for scientific strides, there were also nuances that evidenced potential limitations in both groups. Behavioral psychology has prided itself on its empirical conventions, which has

been evidenced by the strict methods that have been used to measure behavior over the years (Lea, 1978). Using evidence-based practices to carefully manipulate variables and observe changes afforded researchers the ability to test a variety of concepts and make stronger validity arguments for possible links between cause and effect. However, the experimental analysis of behavior stereotypically used single-subject or small-*N* designs, which involved the careful study of few participants or subjects to make conclusions about behavior (Robinson & Foster, 1979). Although the use of single-subjects designs was not inherently problematic, the field of psychology itself trended towards the collection of large samples of participants in order to make research conclusions (Saville, 2008). In doing so, inferential statistics became the norm with which to make more generalizable claims and the meticulous study of few individuals appeared to be left to the behavior analysts and those like them. With that being said, the high value of studying few subjects more distinctly is still warranted, and some behavioral psychologists have even presented methods of making behavior analysis more pragmatic at its foundations (Biglan & Hayes, 1996).

Unfortunately, the study of economics was not immune to both similar and distinct criticisms. Microeconomics concerned itself with the study of individuals and their decision-making processes, and for many, the individual was not enough (Mazur, 2016). For instance, how could the study of one person's purchasing behavior be applied to the market economies at the population level? Perhaps the largest criticism of economics regarding its scientific utility was its lack of empirical grounding (Bickel et al., 1995; Hursh, 1984). Economists, like psychologists, developed methods to measure behavior with the best reasoning available to them, but were deficient in systematic

manipulations and holistically interpreting behavior. Both camps of research asked the question “How much do you value that commodity?” but economics often had difficulty providing an answer that was inherently unbiased. Self-report measures were useful for the purpose of collecting data, but could not be the sole path to understanding behavior. Economics needed to undertake evidence-based methods of measurement and consider alternative explanations for the outcomes they observed. For example, Skinner (1953) discussed the drawback that economists remained well-versed in economics concepts, but not much beyond. Whereas psychology had many branches to lean on to potentially explain their observations, economics was more centralized in its formation. When inconsistencies in human behavior were found in economic studies, economists often attributed these findings to error; behaviorists were able to explain these same findings successfully by considering the influence of other variables. Skinner’s critique was so critical of these shortcomings that he stated economists recognizing and measuring such variables would establish economics as “a complete science of human behavior,” but could not be considered as much until that bar was reached. Although self-report was not the only way economists were measuring behavior, it was clear that using controlled, observable methods substantiated any claims that could be made about behavior and weakened any arguments heading towards circular reasoning.

If economics lacked the empirical rigidity that behavioral psychology held, but also provided a gambit of ecological scenarios to study, why not assimilate the two regions of study? As Hursh (1984) pointed out, subfields of science have leaned on each other to obtain more efficient methods of analyzing information for centuries, and many of those exchanges have not had nearly the same amount of communal interests as

behaviorism and economics. Sharing the same goal of understanding behavior established a minimum baseline of commonalities between the two fields. Consequently, they were able to borrow each other's strengths and meliorate their weakness, producing a more robust method of conducting scientific research that became behavioral economics.

Demand and Reward Valuation

One of the central shared tenets of behavioral economic studies was the concept of demand. Demand has been operationalized in many ways, but is generally defined as the desire for a good or commodity (Hursh, 1980, 1984). A logical basis for understanding the demand for a commodity is to see how much of that thing is being consumed (or purchased), especially as the price or cost of that commodity changes. Price, for humans, can be thought of as a monetary restraint on a commodity or, as in most experimental settings, the amount of work that must be performed to receive access to a reward (Petry & Heyman, 1995). The relation between price and consumption has been well researched in both economics and behavioral psychology. For economists, this typically involved observing trends of consumer behavior over time as market conditions changed (e.g. how much gasoline is being consumed given a $\$10$ increase). For behavioral psychologists, this typically involved manipulating the price of a desired commodity across experimental sessions to see if response patterns changed. Regardless of the type of observer, results generally indicated that there was a systematic relation between the two variables, to the point that a law of demand was proposed (Humphrey, 1996). The law of demand states that as the price for a good or commodity increased, the demand for it, and in turn, its consumption, decreased (Allison, 1979; Hursh, 1980). The

law of demand can also be considered the foundation for determining a demand function: *how much* would consumption change given a change in price?

Another way to think about demand is to conceptualize it as how organisms assign value; what is the worth of a good or commodity to an individual and how far is one willing to go to obtain it? Answering this question is possible through the use of experiments studying both human and non-human animals, albeit purely observationally for the latter. An early objective of behavioral economics was to determine the hedonic (intrinsic) value of a given reward, good, or reinforcer; the process of doing so became known as hedonic scaling (Hursh & Silberberg, 2008; Miller, 1976). For humans, determining the hedonic value for *every* good they consume would be near impossible, especially considering all non-essential ones, and if attempted, would surely take extensive periods of time to measure empirically. Some commodities are consumed regularly whereas others are not; some remain unchanged whereas others are modified. For example, new cellular devices are released almost every year; do people assign different value to the newest edition? If they do, what known and unknown factors influenced these valuations (e.g., new features related to the phone or increases in inflation from year to year)?

Interestingly, changes in consumption with changes in price often showed a curvilinear association, wherein the consumption of a commodity would remain relatively high at low prices, but would slope downward as price increased (Samuelson & Nordhaus, 1985). Researchers who observed this phenomenon also noticed that this slope differed across experimental conditions, specifically when different commodities were presented as rewards or when price values were not congruent. As such, behavioral

economists dedicated time to understanding how and why these curvilinear patterns formed. Among the most useful ways to understand these patterns of behavior was to plot them on graphs and interpolate different information. Typically, the price or cost of a commodity would be plotted on the x-axis, and the consumption of that commodity would be plotted on the y-axis. These plotted demand functions became known as demand curves, and their use became a primary form of behavior analysis for behavioral economists (Hursh & Roma, 2016; Mazur, 2016). Researchers could plot a series of consumption values across a range of prices, through which a line of best fit could be fitted. It is important to note that although the main variables being measured are price and consumption, there must be a moderator (such as the actual act of purchasing or responding in an experimental session) between the two. Demand curves are normally presented in log-log coordinates (both axes logarithmically scaled) due to the range of unit sizes of the variables being measured (such as dollars earned, or food pellets consumed). This demand curve provided a wealth of information: is a demand function even plausible given a combination of variables, at what prices did the subject consume the most or the least, how many data points are necessary to get a complete picture, and at what point does consumption begin to decrease most noticeably? As stated earlier, for most commodities, the slope remained consistently proportionate at low prices; changes in price produced relatively small decreases in consumption. However, as changes in price increased more dramatically, larger decreases in consumption were observed. A 1% change in the consumption of a commodity given a 1% change in its price became known as unit elasticity; for demand curves, this can be directly thought of as a slope of -1 (Raslear, Bauman, Hursh, Shurtleff, & Simmons, 1988). If changes in price produced

small decreases in consumption, the slope would be greater than -1 (e.g., -0.50); this would be considered demand inelasticity. If changes in price produced large decreases in consumption, the slope would be less than -1 (e.g., -1.50); this would be considered demand elasticity. Importantly, the curvilinear relation between price and consumption cannot be represented by a single slope (like in linear regression), as demand curves truly are curves; that is, the rate of change in consumption is not constant across prices. A demand curve where both elastic and inelastic sections are highlighted is represented in Figure 1.

From a theoretical perspective, demand inelasticity and elasticity can be paralleled to low and high sensitivity to changes in price for a commodity, respectively. Imagine if a task was presented to a participant where pressing a button to receive \$1 was made continuously available. At low prices (e.g., “Press this button once, then 15 times, then 30 times, etc.”), responding would likely remain relatively high in order to maintain the same level of consumption; the change in cost (physical act of pressing a button) would not significantly affect rates of consumption. The change from 1 required press to 15 required presses may not feel like a drastic change in effort, and the slight increases in the amount of required button presses would likely not be enough for the participant to slow down when money is at stake. On the other hand, if the amount of required button presses shifted from 100 to 300 to 1000, the participant’s rate of responding would likely decrease accordingly. These shifts in required responding may have felt like too much work to perform for just a dollar; the participant might stop responding completely at such high costs and conclude that the work is just not worth the reward. When presented

with these realistic scenarios in everyday life, people may often ask themselves “Is it actually worth it?”

Although the previous example represented a generic scenario for how elasticity changed in relation to price, a crucial recognition by behavioral economists was that elasticity also appeared to be dependent on the type of commodity being consumed (Hursh, 1984; Raslear et al., 1988). Researchers have noted that some commodities, such as food, water, drugs, and gasoline, tend to be more inelastic even at high prices, given that they are necessities. For example, because gasoline is typically required to drive an automobile, people will pay for it even at higher-than-normal prices. Hursh (1993) found that in the 1970s, gasoline prices tripled in some places (from about ¢30 to \$1.00), but gasoline consumption only decreased by approximately 10%; demand for gasoline remained high regardless of steep increases in price. A meta-analysis conducted by Brons, Nijkamp, Pels, and Rietveld (2008) investigated the elasticity of gasoline prices across varying conditions (type of automobiles, gas mileage, etc.). They found that gasoline consumption was influenced by fuel efficiency across automobile ownership, but that the aggregate gasoline elasticity of the studies was -0.34, indicating that the demand for gasoline was relatively inelastic, or insensitive, to changes in price. The differences in elasticity between necessities and secondary commodities are not set in stone and often vary across samples and experiments. Roma, Hursh, and Hudja (2016) had groups of participants respond about their willingness to spend money on a variety of goods using hypothetical circumstances. The situations to which participants responded were aptly named hypothetical purchasing tasks (HPTs). The respondents were asked to report either the probability of purchasing the items or how many of a specific item

(hamburgers, movie tickets, rolls toilet paper, fine dining meals, a vacation package, or a refrigerator) they would buy at a given price. Demand curves were generated for each participant across the different commodities, and results showed that demand elasticity differed depending on which commodity was being evaluated (where the food items were typically more inelastic and the non-essential items, such as the vacation package, were more elastic). This further illustrated how demand changes not only as a function of price but also depending on the form of the desired commodity.

In addition to changes in the nature of a commodity, other factors, such as the biology of the consumer, can affect demand elasticity. Murphy, MacKillop, Skidmore, and Pederson (2009) conducted an experiment in which a group of participants (with no reported alcohol dependency) was asked to imagine being at a party in which they would be able to purchase 14 different alcoholic beverages of varying prices. These prices were presented in an ascending order, starting at \$0.00 (increasing by 50¢ until reaching the \$3.00 mark, where increments then changed to \$1.00) and ending at \$9.00. The researchers then plotted the amount of alcohol consumed across the varying prices via a demand curve. Results suggested that as the price in dollars increased, the amount of hypothetical alcohol consumed decreased. Alcohol reinforcement in this example was only slightly inelastic (-0.81). In related research, Sumnall, Tyler, Wagstaff, and Cole (2004) presented a HPT to alcohol-dependent participants, asking about how they assigned value to alcohol, as well as other drugs that are frequently misused. They found that for these alcohol-dependents, demand still decreased as price increased, but alcohol was much more inelastic (-0.54) than in Murphy et al.'s (2009) study of non-misusers. Based on these discrepancies, it would seem that elasticity depends not only on what the

actual commodity is, but also the biology (or biological needs) of the consumers themselves. Knowing this, other demand researchers have tested scenarios pertaining to variables with generalizable and realistic implications, such as how drug abusers would respond if drugs were decriminalized (Saffer & Chaloupka, 1999), how nicotine addiction relates to demand (Diergaarde, van Mourik, Pattij, Schoffelmeer, & De Vries, 2012), and the intrinsic value of food in humans (Lappalainen & Epstein, 1990). Findings such as these relating biological components to consumer behavior should be considered when measuring the demand for different commodities.

In contrast to humans, non-human animals have no apparent intrinsic need for commodities beyond those pertaining to biology. Whereas humans have assigned value to things like money, non-human animals typically respond to receive access to natural stimuli (food, water, comfort, and arguably, sexual stimulation), which are often called primary reinforcers (Mazur, 2016). This claim is not presented to ignore the possibility of conditioning responses for other reinforcers (secondary or conditioned reinforcers), but to emphasize the innate demand for primary reinforcers in non-human animals. Kagel et al. (1975) discussed this very fact in an early behavioral economic article advocating for the use of animal subjects to better understand basic economic principles like demand. Kagel and his colleagues drew attention to both the theoretical and practical advantages of integrating non-human animal science with economics and some fallacies with prior methods of approach. First, behavior has always been inherently different across species, but assuming that humans do not share (or are completely separated from) these behaviors would be ignorant. From a scientific perspective, human behavior can be thought of as intelligent, organized, animal behavior, and understanding cross-species

similarities is worthwhile simply for the sake of knowledge. Second, dedicating resources to studying controlled, non-human animal behavior is practical; learning more about behavior itself, especially under stringent, economic constraints, provides concrete information about any underlying processes that may be unexplored. These points are echoed in Kagel et al.'s conclusions, where they state their beliefs that adapting behavioral technologies and methods to study economic concepts would expand the understandings of both fields in a pragmatic and novel way. The recognition that the valuation of shared commodities could be measured using non-human animals provided a turning point for scientists aiming to understand behavior.

Measures of Demand

The experiments and concepts discussed thus far have all centered around behavioral economic research. As mentioned, this newfound confluence of disciplines is rooted in being able to manipulate different environments to observe how (if at all) behavior changes. Many methods have been used to measure demand, but some have appeared in the literature more frequently than others. Hypothetical purchasing tasks, such as those described in Roma et al.'s (2016) experiment above, provided a way to measure demand behavior without requiring many resources or potential risks to participants (e.g., not requiring participants to consume copious amounts of alcohol). A frequent criticism of the utility of hypothetical purchasing tasks is the possible incongruence of self-report with true, everyday behavior. To test this very criticism, Wilson, Franck, Koffarnus, and Bickel (2015) compared the cigarette purchasing behavior of nicotine-dependent participants across both real and imagined conditions. Participants provided information about their smoking habits, and only those who met

DSM-IV dependency status and smoked at least 10 cigarettes a day participated. The experiment occurred in a laboratory setting, where the smokers answered a HPT regarding their preferred brand of cigarettes. They responded to a range of prices for a single cigarette (\$0.01 to \$1120), and then used real money provided by the researchers to purchase cigarettes in a “shop” created in the laboratory. Their findings suggested that the demand curves for both real and hypothetical cigarette consumption were not significantly different from each other, indicating that self-report measures of demand may be just as effective in their ability to quantify behavior as physical experimental manipulations.

Even with the mounting support for applicable measures of demand, such as those generated in HPTs, arguments could still be made that consumer behavior is not truly being measured unless it is directly observed. If one wanted to make claims about the function of demand as objectively as possible, behavior would need to be predictable, manipulable, and measured with as much control as possible. Fortunately, all of these requirements are met through the use of non-human animal subjects in experimental settings. Behavioral economists facing any skepticism for the validity of their measures of demand could present findings on behavior coming from animal laboratories dedicated to maintaining strong experimental control. Animal research could provide a strong validity argument for the demand outcomes that hypothetical tasks simply could not. The obvious criticism of using animals as subjects to measure demand is simultaneously its greatest strength: an animal cannot say what it is thinking or how much it would be willing to pay for a pellet of food, but it can show how much it values something through its behavior. The ability of animals to exhibit their motives without the need for

verbalization may provide insight into behavioral processes that underlie all behaving organisms.

Schedules of Reinforcement

The practice of using non-human animal subjects was popularized by behavioral psychologists in the mid-1950s (Mazur, 2016). Although other behavioral psychologists were also prevalent at the time, Skinner in particular became popular for his approach to studying animal behavior in laboratory settings. One of Skinner's largest contributions was his creation of the cumulative record and his analysis of behavior under various schedules of reinforcement. Schedules of reinforcement pertained to studying how animals behaved when certain conditions had to be met in order to receive access to reinforcement (typically food). Animal subjects' responses, such as rats pressing levers or pigeons pecking keys, provided information about patterns of behavior when operating under these rules. Skinner plotted these animals' responses using his cumulative record, which was a continuously scrolling roll of paper with a pen or pencil attached to the roll on one end. As animals made responses on their respective devices, the writing tool would touch the paper and slowly move upward with each response; as time passed, the accumulation of data could be analyzed for an entire experimental session, showing both peaks and latencies in response patterns. These foundational measures translate directly to behavioral economic analyses of behavior conducted a few decades later, specifically measuring patterns of responses and consumption under restricted conditions.

Four primary schedules of reinforcement were studied by Skinner: fixed-ratio (FR), fixed-interval (FI), variable-ratio (VR) and variable-interval (VI) (Mazur, 2016). All schedules of reinforcement involved receiving access to a reinforcer in some fashion,

albeit under different conditions. Under fixed-ratio schedules, an exact number of responses needed to occur before access to a reinforcer became available. For example, on an FR60, a reinforcer, such as a sugar pellet, would be provided after the 60th response was made. Under fixed-interval schedules, an exact amount of time needed to pass before a reinforcer became available; responses could be made during the interim, but only the first response after the allotted time requirement would provide a reinforcer. In contrast to fixed schedules of reinforcement, variable schedules of reinforcement are not static across an experimental session. Under variable-ratio schedules, a reinforcer becomes available after an average number of responses is made, but this number is not constant from reinforcer to reinforcer. For instance, on a VR60, the responses required for the first reinforcer might only be 10, but responses required for the second may be 90; the number of responses simply needs to average to the value of the schedule across the testing session. Finally, a variable-interval is similar to a fixed-interval schedule with the exception that the amount of time that passes before a reinforcer becomes available is unpredictable for the subject. For example, on a VI60 schedule, a response could be reinforced after 5 seconds or 80 seconds, so long as the average of those trials equals 60.

The schedules presented here are all useful ways to measure behavior, but most are problematic if research questions specifically wish to test response frequencies under different experimental conditions. Both of the variable schedules have the caveat of unknown variability, and any interval schedule must consider the effect that time might have on patterns of behavior. Though the factor of time is present when subjects operate under FR schedules (i.e., time passing between responses), it is inherent to the procedure rather than an actual manipulation. If a researcher were trying to measure responding

alone, utilizing a fixed-ratio schedule would be most beneficial. Fixed-ratio schedules only require that a specified number of responses have occurred, after which access to a reinforcer becomes available. In the experimental analysis of behavioral economics, the use of fixed-ratio schedules has become synonymous with price. Specifically, demand for a commodity (food) can be directly measured by collecting response rates (how much the animal is willing to “pay”) in an experimental session. Equating fixed-ratio schedules to price provides a theoretical connection between animal and human behavior; how different is an FR50 schedule requiring a rat to pull a lever to receive food from a human being charged \$50 for a fine-dining meal?

Schedules of reinforcement can also be presented concurrently; in doing so, the possible effects of commodity alternatives on demand can be seen using animal subjects. Carroll, Carmona, and May (1991) trained rhesus monkeys to self-administer either phencyclidine (better known as PCP) or saccharine water, which were both simultaneously available under differential fixed-ratio schedules. During a period of testing sessions, PCP had an ascending series of FR values assigned to its access (FR4, FR8, FR16, FR32, FR64, FR128), while the saccharin water was held constant (FR16). These same conditions were reversed as to switch the FR schedules of PCP and saccharin water. Results from both experiments provided seminal information about how more factors needed to be considered when measuring demand. Relatively speaking, both PCP and saccharin water were elastic (changes in price caused larger decreases in consumption). Furthermore, when PCP was presented on an increasing FR schedule (also called a progressive-ratio schedule) with saccharin water available on an FR16 schedule, PCP self-administration decreased by up to 90% of baseline levels. In contrast,

when PCP's price was held constant and saccharin's price increased, PCP self-administration only decreased by around 10%. These results speak once again to the role of price in the demand for a commodity, but also highlight the importance of considering the availability of other reinforcers.

The behavioral fundamentals of FR schedules made the integration of behaviorism and economics easier given its functional usage to measure demand. The variables of interest (price and consumption) are inherent to these measures of behavior, sometimes quite literally in the latter's case. The applicability of ratio schedules should not be overlooked in their ability to objectively measure demand because of their laboratory conditions or use of animal subjects. With that being said, known factors that influence demand in other settings must be assessed when experiments use animal subjects. For example, research concerning hypothetical purchasing behavior in humans had implications that the commodity being worked altered consumption outcomes. Food and drugs are frequently used in tandem with FR schedules, but what if responses on the schedules differed due to the commodity being worked for? Similarly, it is important to have identified plausibly impactful factors that are specific to FR schedules. Collecting information about the number of responses that occur at a given FR price is the basis for demand experiments using animals. Factors such as interresponse times (IRTs; the amount of time that has elapsed from one response to the next) and post-reinforcement pauses (PRPs; the amount of time that has elapsed since receiving the last reinforcer) are related to response frequency and should be considered when making conclusions about demand. Morse (1966) pointed out that low FR values typically relate to smaller IRTs; if this is the case, demand elasticity could be dependent on how fast the subject was

responding and not just how much it was responding. Lengthier post-reinforcement pauses could be due to the animal being satiated, fatigued, or even preparing to make a large number of responses (Mazur, 2016). If this is the case, the animal's demand for a commodity at higher prices may actually be high, but might be confounded by factors outside of experimental control. Even with the multitude of variables to consider, FR schedules of reinforcement still offer a methodological approach to measuring demand behavior. Response patterns under these schedules afford the researcher detailed information about how changes in consumption change across varying prices, which can be used to analyze different dependent measures.

Behavioral Economic Formulae

In the pursuit of better quantifying a demand function for the relation between price and consumption, behavioral economic researchers developed multiple formulae that better aim to capture different parameters of interest. The first, and most simplistic of these, is equivalent to the demand function presented earlier (i.e., demand elasticity) when in percentage form. The formula is simply the percentage change in consumption (Q) over the percentage change in price (P).

$$\text{Demand Elasticity} = \frac{\% \Delta Q}{\% \Delta P} \quad (1)$$

When examined as non-percentages, this same formula simply becomes the relation between consumption and price. For example, if a subject responded 1000 times on an FR100, the subject would receive 10 reinforcers. This formula provides a foundation for understanding demand in a given testing session and allows the researchers to quantify

any differences between consumption data points, but does not provide a way to systematically evaluate the *rate* of change in demand elasticity.

Another formula, which produced a more detailed picture of the many parameters influencing demand, was developed by Hursh, Raslear, Bauman, and Black (1989) and is called the linear-elasticity equation, represented below

$$\ln Q = \ln L + b(\ln P) - aP \quad (2)$$

where Q , as in the demand elasticity formula above, represented consumption, and P once again represented price. L was the level of consumption as P gets closest to 0, b was the slope of the demand curve “after an infinitesimally small increase from a zero-level price,” leaving a as a coefficient (Hursh & Silberberg, 2008). After reduction, this formula simplifies to the slope (b) minus the product of a and the price (P), which consistently provided a strong model fit when used across different commodities. However, this equation was deemed problematic by some behavioral economists because of its inclusion of two free parameters (a and b) in their approximation of demand elasticity changes. More specifically, if b (which as mentioned above, is assumed to be near 0) is in fact, set to 0, it has catastrophic effects for model fitting/effect sizes.

To meliorate this issue, Hursh and Silberberg (2008) developed a formula that could determine demand elasticity using only one free parameter and maintained model fit at and above that of the linear-elasticity equation: the exponential-demand function. The formula presented below includes Q , which again is consumption, Q_0 , which is the assumed hedonic value (consumption if price were 0) of the commodity, k , which is the

range of the consumption values (this would be a constant), and α , which indicates the rate of decline in consumption as price increases.

$$\log_{10}Q = \log_{10}Q_0 + k(e^{-\alpha Q_0 P} - 1) \quad (3)$$

This formula provided a stable model that could be fit to demand data, while simultaneously providing more information than any of the formulae used before it. For example, Q_0 provided a hypothetical value for what the consumption of a commodity would be if it had no cost associated with it; this was the same pursuit as hedonic scale mentioned previously and is often called demand intensity. Furthermore, α , a generated measure of demand unit elasticity, allowed behavioral economic researchers to determine the rate at which consumption decreases with increases in price (Fragale, Beck, & Pang, 2017). From α , a different value, P_{max} could also be inferred, which is the price at which maximum responding occurs by the subject; past this point, the slope of the demand curve becomes more negative than -1. P_{max} provided an excellent estimation for the price point where consumption begins to decrease more rapidly or become more elastic; the reward may no longer be worth the cost associated with it. Although typical statistical analyses (such as regression or analyses of variance) are still used in the experimental analysis of demand behavior, the exponential demand function allowed behavioral economists to identify parameter estimates (providing a better picture of behavior) that are most useful to those describing economic concepts.

Open vs. Closed Economies

Behavioral economic experiments measuring demand using non-human animal subjects have brought attention to the possible effects of the environmental conditions on

behavior. Specifically, will response patterns change depending on whether the subject is operating under different environmental conditions, such as either an open or closed economy? An open economy exists when an animal subject is able to receive food by working for it during experimental procedures, but is also provided supplemental food outside of the testing environment. In contrast, a closed economy exists when animal subjects are *only* able to receive access to food through their testing performance; no other food is provided. Hursh (1980) was the first person to coin the terms “open and closed economies” when describing the economic system that animal subjects were operating in during experimental procedures. In his seminal review, Hursh described the results of previously published research that used animal subjects under differing conditions. Multiple experiments using FR schedules to measure demand presented different findings of consumption rates, but the engine behind these findings was uncertain. Animals (both rats and pigeons) that were tested in these studies were similarly food deprived, exposed to the same schedule of reinforcement, and were tested for the same length of time. Hursh ruled out these experimental manipulations as possible confounds, but pointed out one integral modification across the studies: the differing types of economies (i.e., an open or closed economy) the researchers exposed the animals to during experimental procedures. The animals were placed in testing conditions where their work for food was potentially being influenced by an uncontrolled factor intrinsic to the researchers’ decisions about what goes on outside of those conditions. For the most part, the experimental analysis of behavior had been inherently using open economies in their research (Hursh, 1980). However, if the impact of the type of economic setting the animal is operating in has a distinct influence on responding, it

should be controlled for whenever possible, or at least tested across both economies.

Although Hursh's goal was not to discredit all experimental results that operated under open economies in the past, he did highlight an important implication for both the reliability and validity of behavioral data collection, especially data pertaining to behavioral economics. Demand experiments (using fixed ratio schedules as a measure of price) operating under a closed economy would often find that consumption of food was more inelastic across increasing prices (Collier, Hirsch, & Hamlin, 1972; Hursh, 1980). When the only way to receive food, a biological necessity, was to work for it, organisms responded more frequently at higher prices than under open economic conditions. What differences in response patterns were occurring across economies and what factors could be causing these differences?

To answer this very question, Collier, Johnson, and Morgan (1992) performed an experiment in which a group of Sprague-Dawley rats performed a lever-pressing exercise in both open and closed economies. Rats responded on an FR10 and an FR40 schedule and received either small, medium, or large food pellets for their work; all of these factors were crossed and rats were exposed to each pair of manipulations (e.g., FR10 with small food pellets, FR40 with small food pellets, FR10 with medium food pellets, etc.). In one condition, the rats were in a closed economy, only receiving food for pressing a lever, although their consumption was unrestricted. In a second condition, the rats operated under a closed economy again, but their weight was restricted to 85% of their free-feeding body weight; this manipulation was used to see if weight (or food deprivation) had an influence on response patterns. Finally, a third condition placed rats in an open economy, but under restricted weight control like the second condition. Their

results indicated that there was an interaction between their variables of interest: the effect of pellet price on the frequency of responses depended on whether the rats were in an open or closed economy. Responding was higher in both of the closed economies at the lowest prices, regardless of restriction, but not in the open economy. The response patterns provided by the rats also indicated that when they operated in a closed economy under restricted food access, they responded more frequently than when in an open or closed economy with unrestricted access to food.

Collier et al. (1992) interpreted these results to mean that when operating in closed economies, food's availability is perceived as relatively scarce, and as such, the rats responded faster to obtain more food, regardless of its cost. If there is only one way to receive access to a commodity, subjects are more than willing to expend more effort to obtain it. Collier et al. suggested that others measuring demand should consider the effects that the type of economy may have on their results, and more importantly, their interpretations of those findings. These suggestions are consistent with other behavioral literature that has implied value is higher for rewards that are guaranteed or more immediate. For example, Green and Myerson (1996) have conducted experiments with non-human animal subjects that found rewards that are temporally further from being obtained have lower value. These results also support Carroll et al.'s (1991) findings about PCP consumption: the availability of other reinforcement opportunities (i.e., receiving food outside of the testing environment) influenced demand. In conclusion, Collier et al.'s (1992) findings provided important information regarding the influences of open and closed economies on consumer behavior, namely that demand under

restricted conditions generally produces higher rates of responding and may be more representative of an animal subject's true valuation of a commodity.

Rapid Demand Curves

The culmination of the previously discussed behavioral economic principles converges in a series of experiments conducted by Raslear et al. (1988). The purpose of their experiments was to determine a demand function for the relation between price and food consumption using animal subjects. The authors provided a general overview of behavioral economic principles, such as fixed ratio values serving as price, closed vs. open economies, and demand elasticity. Alongside this information, they posited that the identification and construction of demand curves not only provides information about the relation between price and consumption, but also about what other variables might be influencing those outcomes (e.g., how demand changes as a function of motivating operations). Within their description of the usefulness of demand curve generation, the researchers pointed out one of the biggest issues of utilizing psychological methods to analyze behavior: the amount of time necessary to collect complete, reliable data when using non-human animal subjects. For example, Hursh (1984) suggested that when measuring consumption using FR schedules, each schedule's evaluation should last approximately 30 to 40 days for reliability purposes; to collect enough information to fit models to these data, observation periods could last half a year.

Given this substantial pitfall in the efficiency of demand curve generation, Raslear et al. (1988) conducted three similar experiments aimed at determining if reliable demand functions could be acquired in a short period of time (7 days) compared to data collection that typically takes weeks. For each of their three experiments, the researchers presented

groups of Sprague-Dawley rats with varying FR schedules. These rats were also operating under a closed economy, where access to food was only available during experimental sessions. By forcing the rats to respond for access to food, the value of food and its rate of consumption could be directly measured and attributed to changes in the amount of responses required to gain it. Raslear et al. did not explicitly present their reasoning for using the FR values that they did (i.e., FR1, FR15, FR45, FR90, FR180, FR360), but it can be inferred that the values were chosen based on both previous research and for pragmatic purposes. In order to realistically measure a demand function, a range of values would simply need to be chosen, and choosing extreme values, like an FR1000, would likely be too costly for the organism to respond. The apparatus with which to measure this behavior was also consistent across experiments: a single response lever, a food magazine to deliver reinforcers, and a mounted water bottle, which was freely available. For the purposes of analyses, the authors measured food consumption, responding that occurred during both the day and nighttime (used to make analogies about circadian rhythmicity), inter-response times, post-reinforcement pauses, and the rats' weights. Inter-response times and post-reinforcement pauses were measured to obtain a better picture about how the animal subjects were distributing their behavior across a given session; for example, responses on less costly conditions may occur more rapidly and frequently than at higher costs.

Typically, animals that have extended periods of time to adapt to experimental manipulations achieve behavioral stability (their responding under given conditions is consistent or has low variability). Stability in behavioral experiments is often suggestive that behavior is reliably being influenced by experimental conditions in the same manner

over time. However, it is possible that a rapid procedure would not allow for this stabilization to occur like in a prolonged procedure, consequently making interpretations of data dangerous. As such, the general method described above was used to assess any potential changes in consumption in relation to experience with the procedure (Raslear et al., 1988). This first experiment tested a group of 6 experimentally naïve rats multiple times to ensure that performance under speeded conditions was comparable to data collected over lengthier conditions. Each day of the procedure had an FR requirement assigned to it, beginning with an FR1 for Days 1 and 2, FR15 on Day 3, FR45 on Day 4, FR90 on Day 5, FR180 on Day 6, and ending with an FR360 on Day 7. The first FR1 was utilized as an acclimation period to control for individual variability in acquisition of the lever press response and was not included in any analyses. Rats repeated this ascending sequence of conditions 4 times (7 days for each iteration for a total of 28 days), restarting with an FR1 after the end of the previous week's FR360. This allowed for the identification of any potential testing effects that may have occurred due to repeated exposure (or lengthier conditions).

The results of the first experiment indicated that the rats produced nearly identical demand curves (both quantitatively and qualitatively similar) over all four replications. These demand patterns were also like previous findings observed in the same laboratory, providing evidence that data collected in a week's time was congruent with data collected over extended periods. Furthermore, inter-response times and post-reinforcement pauses were relatively invariant across changes in price, which may have implications for the robustness of required responding under restricted conditions. Statistical results of the effect of the FR schedule manipulation on changes in consumption indicated that the FR

schedules significantly explained the most variance in food consumption (approximately 25%). However, a significant interaction was found between replications and the FR schedules on consumption, where consumption was higher for later replications. This interaction for the increasing amounts of consumption was attributed to the natural growth of the rats, as well as the drastic change in price from an FR360 back to an FR1 over the transition between repetitions.

Although the information provided by the first experiment supported the use of a rapid procedure, Raslear et al. (1988) wanted to provide further validity evidence for these results by conducting two experiments designed to rule out possible confounds, such as the presentation order of the FR schedules (ascending vs. random) or the size of the steps between prices (1 to 3 rather than 1 to 15). As previously mentioned, demand law states that as the price of a commodity increases, its rate of consumption decreases (Allison, 1979; Humphrey, 1996). If this is true, presenting a low price as the first experimental condition may considerably change consumption outcomes in later steps. For example, will the demand patterns of animals beginning on an FR180 differentiate from those that began on an FR90? To test this, the researchers repeated their first experiment over a week's time using two separate groups of naïve rats, one group receiving the controlled ascending order of the same FR values from the first experiment, and another using a randomized presentation order of those FR values. The randomized presentation was fully counterbalanced, meaning that every combination order of FR values was tested on a set of rats. Similar to the first experiment, the researchers found a statistically significant main effect of the FR schedule, demonstrating that regardless of

whether the treatments were presented in an ascending sequence or randomly, changes in price were explaining the most variability in food consumption.

With findings supporting both the use of a rapid procedure and a resistance to sequential effects, Raslear et al. (1988) finally aimed to exclude step size (i.e., the amount of change between price conditions) as the reason for changes in consumption; perhaps large shifts in work requirement across conditions were the reason for the observed response patterns. To do so, two more groups of naïve rats were tested over a single week, with one group experiencing the same ascending FR sequence as in the first two experiments, and the other experiencing an ascending sequence of FR1 (twice), FR3, FR9, FR27, FR81, and FR243. It is important to note that their goal was not to change the FR values themselves, but how large the change between conditions was (i.e., a difference of 2 from an FR1 to an FR3 compared to a difference of 14 from an FR1 to an FR15). These results further supported the stability of the rapid demand procedure; both groups of rats produced similar consumption patterns (quantitatively and qualitatively), and the FR schedules explained the most variance in consumption. For this experiment and all previous ones, responding occurred more frequently during the nighttime, which is intuitive given that rats are nocturnal organisms.

In their general discussion, Raslear et al. (1988) interpreted their findings and provided suggestions that the generation of demand curves using animal subjects was not only possible to be completed in a week's time, but resistant to experimental manipulations such as sequence effects or changes in step size. From a theoretical basis, these observations follow the law of demand, where the rats generally consumed less food as price increased across all experiments. From a practical standpoint, the

researchers utilize their findings to discuss this method as an efficient behavioral measurement tool. The ability to collect a complete, reliable set of data in a week's time is beneficial to a range of scenarios. For example, a substance abuse rehabilitation center that may typically need weeks to assess the behavioral patterns of an addict may be able to rapidly determine just how much they are willing to spend for their drug of choice when time is of the essence. In an experimental setting, the effectiveness of the procedure's rapidity could translate to more quickly understanding the effects that a new drug might have when introduced with other manipulations. Moreover, the general invariance of the other measured variables (inter-response times, post-reinforcement pauses, etc.) led Raslear et al. to suggest that the impact of potential covariates pertinent to other scientists can easily be assessed using this approach while also creating demand curves.

Research Questions

It is evident that the convergence of economics and experimental behavioral psychology has provided researchers a more systematic and empirically based method with which to assess behavior. Through this integration, behavioral economists have been able to measure economic outcomes using highly controlled experimental situations. Specifically, behavioral economics seeks to identify general principles of behavior that may span across all species. Of these possible general principles is the valuation of different commodities. For both human and non-human animal subjects, commodities hold different levels of value, with the demand for them constantly changing depending on the commodity itself, the restraints it is presented under, and the biology of organism working to consume it. For example, one could be asked how much a scoop of ice cream

is worth in dollars, and the answer would likely vary given the season of the year, the flavor of ice cream, or even whether the person is lactose intolerant. The previous example may seem trivial but speaks to the importance of being able to determine a fundamental understanding of how demand works. If we hope to predict the value of a commodity across varying scenarios and how the demand for it changes, we must first identify if there is an orderly basis that crosses a variety of environments, organisms, and manipulations. By doing so, a more complete picture of how behavior can best be predicted, controlled, and explained is formed, and can be utilized for the endeavors of both basic and applied science.

Given this goal, it is necessary to create an experiment that provides further evidence for a fundamental demand function describing the relation between the price and consumption of a commodity. Although demand is only one component of many that is studied in the field of behavioral economics, it is one that can be directly manipulated and observed in experimental conditions. Experimental methods have been used frequently to measure demand in non-human animal subjects, but these methods typically use the same animal subjects (rats, mice, and primates), do not control for many of the previously discussed covariates (i.e., biology, alternative reinforcers, open vs. closed economy, type of reinforcer) and require extensive data collection time to observe reliable results. The previously presented findings have evidenced how the manipulation of a single variable can alter response patterns throughout entire procedures, leading to different conclusions. Although altering these conditions provides beneficial information about specific research questions, they also identify a clear gap in the study of demand behavior.

The primary purpose of the current experiment is to replicate and build upon the methodological approach and findings of Raslear et al. (1988). There is a substantial body of research measuring the relation between price and consumption, but to my knowledge, there is currently no published literature that explicitly replicated the methods presented by these authors. The experimental checks conducted within Raslear et al.'s study provided some validity evidence for a method of rapid demand curve generation and the usage of the outcomes pertaining to it, but a streamlined replication using different animal subjects could further support their findings. Through the replication of these methods, I hope to answer two research questions regarding the principles of economic demand. First, can a demand function be determined under the restricted conditions of a closed economy? In other words, will the food consumption patterns of pigeons exposed to increasing FR values have a systematic outcome that can be observed? If so, can these consumption patterns be collected rapidly and still resemble behavior shown by other animal species (rats) that have experienced these rapid conditions? Given the distinct effectiveness of Raslear et al.'s (1988) experiments, I hypothesize that all pigeons will be able to evidence clear decreases in consumption across incrementing prices within a shortened period of time. In doing so, evidence for cross-species similarities could highlight the possibility of an underlying mechanism of demand that may be inherent to many organisms.

Method

Subjects

Six White Carneaux (Columbia Livia) pigeons were used as test subjects. All pigeons were adults of unknown sex purchased from the Palmetto Pigeon Plant, SC. The

subjects were not experimentally naïve. When not participating in ongoing procedures, all subjects were individually housed in stainless steel cages that are 15 in. (381mm) in length, 9 in. (228.60mm) in width, and 13 in. (330.20mm) in height. Both the housing room in which these cages were held and the operant room in which experimental sessions occurred have a 12-hour day-night light cycle, a humidity maintained between 30% and 70%, and a temperature range between 68° and 76° Fahrenheit. Prior to the start of the procedure, the pigeons were deprived of food (to evoke responding during the procedure), and their weights were maintained between 80 and 85% of their free feeding weight. Free access to water was provided throughout this deprivation period and during all experimental procedures.

Apparatus

The experimental sessions were conducted in Med-Associates' rodent/pigeon operant chambers (Product ENV-007), which are 11.63 in. (295.40mm) in length, 9.25 in. (234.95mm) in width, and 10.75 in. (273.05mm) in height. Each operant chamber, which houses an individual subject, was located in its own attenuating box that is 25 in. (635mm) in length, 18 in. (457.20mm) in width, and 23.50 in. (596.90mm) in height. These attenuating boxes were designed to block any outside light and sound, and provide ventilation to the pigeon. Experimental components of the operant chambers included a houselight, used to illuminate the chamber during daytime procedural periods, as well as a single lit operant key to which the subjects could respond. Additionally, a pellet dispenser (Product ENV-203-45) delivered food pellet reinforcers (Bio-Serv Dustless Precision Pellets, 20mg) to a trough located within the chamber. A stainless-steel trough filled with water was placed on the floor of the operant chamber so that the subject could

have ad libitum access during the procedure. This water trough was placed opposite adjacent to the operant key.

Furthermore, each attenuating box contained a security camera (Lorex PTZ) that was mounted above the operant chamber and centered on the subject. This allowed the researchers to remotely monitor all experimental sessions via mobile application. Behavioral experiments involving animal subjects typically occur in 1-to-3-hr sessions; remote monitoring provided security for the animals' well-being throughout the extended procedure length. As the procedure occurred during both day and night, an LED Infrared Light (JC Infrared Illuminator) was placed inside the boxes to aid the cameras in capturing images during nighttime hours when there was no other light available within the operant chamber.

Procedure

Prior to beginning the first experimental session, the researchers weighed the subjects to ensure that they were within their deprivation range and were of healthy status. The procedure ran for exactly 23 hr and 30 min a day for a total of 5 consecutive days, starting promptly at 10:00 A.M.. Although maintaining a closed economy was essential to experimental control, the well-being of the subjects was the highest priority. As such, sessions ended at 9:30 A.M., wherein the researchers removed all subjects from their operant chambers, weighed them, and returned them to their housing cages located in the housing room. During the 30 min that the subjects were in the housing room, the researchers sanitized the operant chambers, refilled all water troughs, and ensured that all equipment was working properly.

Upon entering the operant chamber, both the houselight (Product ENV-315W) and operant key (Product ENV-123A-O) illuminated to signal to the subject the start of the procedure. The operant key was illuminated throughout the entire session (save 2 sec to account for pellet delivery and consumption) and any responses to the lit key were recorded. A pellet dispenser (Product ENV-203-45) provided food pellets via a trough located below the operant key once the appropriate number of responses occurred as determined by the FR value for that experimental session. In contrast to the operant key, the houselight was used to illuminate the operant chamber to closely mirror the 12-to-12-hour day-night cycle maintained in the subjects' housing room. The light remained on for 5 hr and 55 min from the start of the procedure, turned off for 11 hr and 45 min, then turned back on for 5 hr and 50 min until the end of the procedure. This ensured that the subjects received equal amounts of day and night regardless of their health check removal.

The main manipulation of the FR schedule was in effect from the start of the procedure. In order to receive a single food pellet, the subject was required to peck the lit response key the exact number of times on the given schedule. Preliminary tests of fixed-ratio schedules for the pigeons used in the current experiment indicated that responding on an FR1 resulted in unexpected outcomes. All pigeons vomited within the operant chamber after spending a day responding with continuous reinforcement (FR1). Response rates were relatively high for the FR1 ($M = 2959$, $SD = 359.80$), but potential carryover effects were evident for the next day's procedure, wherein all pigeons either responded very little (<100 responses) or not at all. As such, all subjects began on an FR15 schedule of reinforcement the first day of the procedure, followed by an FR45,

FR90, FR180, and FR360 for each subsequent day, respectively. The removal of this experimental condition reduced the length of the procedure from 7 days to 5 days.

Responding during the day (Daytime Responses or DTRs) and night (Nighttime Responses or NTRs) was measured separately to be used as a measure of circadian rhythmicity. Inter-response times and post-reinforcement pauses were also measured separately during day and night hours. Any daytime inter-response times (DIRTs) or post-reinforcement pauses (DPRPs) that began during the daytime and carried over into nighttime hours were recorded as a daytime measure. In contrast, any nighttime inter-response times (NIRTs) or post-reinforcement pauses (NPRPs) that carried over into daytime hours were recorded as a nighttime measure. After the subjects completed all 5 days of the procedure, they were returned to their home cages and received free access to food.

Results

A one-way repeated measures ANOVA was conducted to assess differences in consumption across all FR conditions, with alpha set at .05. One subject, Pigeon 9, was removed from this and all subsequent analyses due to experimenter error (which negatively influenced response rates), leaving 5 total subjects. A Greenhouse-Geisser adjustment was used as Mauchly's test of sphericity provided evidence that the assumption was violated, $\chi^2(9) = 26.71, p = .005$. Table 1 presents descriptive statistics for consumption values across all experimental conditions. There was a significant effect of FR condition on consumption, $F(4, 16) = 32.06, p < .001$, partial $\omega^2 = 0.86$ (see Table 2 for ANOVA values). The omega-squared effect size estimate was relatively large, where 86% of the variability in consumption could be explained by the variability in FR

conditions. Pairwise post-hoc analyses using a Bonferroni adjustment were also conducted, evidencing that there were significant differences in consumption between the FR15 condition and the FR90 ($p = .028$), FR180 ($p = .011$), and FR360 ($p = .010$) conditions, but no significant differences between any other pairs of FR manipulations (all p 's $\geq .54$).

Multiple one-way repeated measures ANOVAs were also performed to see if differences in interresponse times, post-reinforcement pauses, and weight occurred across FR conditions. There were significant differences for only daytime post-reinforcement pauses, $F(4, 16) = 4.41$, $p = .014$, $\omega^2 = 0.39$, and subjects' weights, $F(4, 16) = 4.86$, $p = .047$, $\omega^2 = 0.42$. Mauchly's test of sphericity indicated that sphericity was not violated for daytime post-reinforcement pauses, $\chi^2(9) = 9.05$, $p = .539$, but was violated for subjects' weights, $\chi^2(9) = 25.78$, $p = .007$, so a Greenhouse-Geisser adjustment was used when analyzing weight data. All other demand measures (day and nighttime interresponse times and nighttime post-reinforcement pauses) had $p \geq .255$.

The exponential demand equation (Hursh & Silberberg, 2008) was used to fit a demand model to each subject's data and create visual representations of demand curves via the software program GraphPad Prism 8 (San Diego, California). This software provided both parameter estimates for all subject's response patterns and demand curve graphics. Consumption values of 0 are problematic for model fitting when using the exponential demand equation, as the values need to be scaled logarithmically, so these values were transformed to 0.001 (this occurred for only one subject, Pigeon 1, at the FR360 condition). Values of demand intensity (Q_0) and demand elasticity (α) were able to be determined using the exponential demand model, indicating each subject's

hypothetical value at a price of 0, and the rate of negative acceleration in the demand function, respectively. The Analytic P_{\max} Calculator (Gilroy, Kaplan, Reed, Hantula, & Hursh, 2019) was also used to determine the point of unit elasticity, which indicated the place along the demand curve at which each subject's consumption slope hypothetically becomes more negative than -1. See Table 3 for parameter estimates from the exponential demand equation.

Visual analysis was used to examine both qualitative and quantitative shifts in consumption patterns for the animal subjects. All subjects except for one (Pigeon 7, with one outlier data point) had consecutively decreased consumption as FR values increased. Figure 2 represents the demand curves for each individual subject and Figure 3 represents the average demand curve for all 5 subjects together. Table 4 depicts how these consumption values changed across the FR manipulations by subject, alongside the average PRPs and IRTs. Exponential demand models generally fit the data extremely well, where three subjects (Pigeons 3, 5, and 8) had R^2 goodness of fit values above 0.90, and an average effect size of $R^2 = 0.83$ for all 5 subjects together (although individual variability is evident as expected; see Table 3).

Discussion

The current experiment's primary goal was to replicate and provide empirical support for Raslear et al.'s (1988) study by using pigeons in a rapid demand procedure. Raslear and his colleagues found that rats produced reliable demand curves in a week's time that would normally take extensive periods of data collection to be considered stable. Fortunately, the field of behavioral economics is not lacking studies of demand behavior with non-human animal subjects. However, little to no research has aimed to

recreate these findings using different animal species, which is unusual, especially given how pragmatic these methods could be.

The results of the current experiment indicated that the behavior of the pigeon subjects generally followed the law of demand: as the price of a food pellet increased from an FR15 to an FR360, rates of consumption decreased. A key concern for both Raslear et al.'s (1988) experiment and the current experiment was the maintenance of a closed economy, ensuring that the subjects only received food while within the testing environment. In order to keep the pigeons within a healthy weight range as per protocol, Pigeons 1, 7, and 8 broke the closed economy and were fed outside of the procedure, while Pigeons 3 and 5 remained in a closed economy. Pigeon 1 and Pigeon 8's demand curves appeared to become more elastic at lower prices. In contrast, Pigeon 3 and Pigeon 5's demand curves appeared to remain relatively inelastic until the more costly conditions. These findings correspond with Collier et al.'s (1972) and Hursh's (1980) results, in that food remained relatively inelastic for the pigeons who maintained a closed economy. Pigeon 7's consumption value at an FR45 seemed to be inconsistent with the rest of its consumption pattern, which is also evidenced by its relatively lower model fit ($R^2 = 0.63$). This potential outlier is likely due to an adverse event that occurred prior to the start of that condition's procedure (see Limitations), but may also be a true representation of the subject's demand for that FR manipulation. Although this subject's demand curve appeared to be more similar to that of Pigeons 1 and 8 (especially at higher prices and given its broken economy), making conclusions about its true pattern of demand may be biased because of this irregularity.

Although no direct comparisons of data were made between this experiment and Raslear et al.'s (1988) experiment, visual representations suggested that the demand patterns of the pigeon subjects were both qualitatively and quantitatively similar to that of the Sprague-Dawley rats in the original study, although consumption for the pigeons appeared to be slightly higher. Likewise, IRTs for both the current experiment (DIRTs and NIRTs) and Raslear et al.'s did not differ significantly across changes in price, but PRPs did (specifically DPRPs in the current experiment). Theory suggests that post-reinforcement pauses may increase in length because the subject has learned that the upcoming response requirement will require a large amount of effort/be costly (Mazur, 2016). For example, a pigeon responding on an FR180 schedule may have learned that after 180 responses, it will need to perform another 180 to receive another reinforcer, and as a result, wait longer to begin responding. Given the progressive increase in FR requirements in the current procedure, it follows that significant differences in DPRPs would exist. The Sprague-Dawley rats in Raslear et al.'s original experiments typically responded more during the nighttime, which follows logically as rats are considered nocturnal organisms. However, Raslear et al. cautioned that these measures of circadian rhythmicity were variable across their experiments. In contrast, the pigeons (which are considered diurnal) in the current experiment responded most frequently during the daytime.

As mentioned previously, the exponential demand equation evidenced moderate to strong model fits for all animal subjects. Pigeons 3, 5, and 8 had large effect sizes, while Pigeons 1 and 7 had moderate effect sizes. Although larger effect sizes are not atypical in repeated measures operant experiments, the strength of these effect sizes

speaks to the utility of the rapid demand procedure. Even with the removal of two testing days and differences in whether the closed economy was broken, the exponential demand equation was able to encapsulate each subject's demand patterns. Values for demand intensity and unit elasticity were able to be generated for all subjects, providing a detailed picture of individual differences in demand. Determining these values helped better quantify a demand function between consumption and price, an objective shared by both this experiment and Raslear et al. (1988). The demand curves for both the individual subjects and the aggregate data in the current experiment showed clear shifts in sensitivity/elasticity as price increased. The generally low unexplained variability for consumption, as well as the ability to estimate these unknown parameters, may be indicative of the subjects' actual valuation of food. Unfortunately, Hursh and Silberberg (2008) had not yet created the exponential demand equation when Raslear et al.'s (1988) experiment was conducted, so it was not possible to compare parameter estimates between that experiment and the current one.

Limitations

Although the current findings encouraged the use of rapid methods to collect demand data, multiple limitations may have influenced the outcomes and their interpretability. Due to the preliminary findings that all pigeons vomited when operating under an FR1 schedule of reinforcement, this experimental manipulation was removed from the current procedure. The removal of this condition restricts the ability to make exact comparisons of demand between this experiment and Raslear et al.'s (1988). Explicitly, the demand curves between the experiments are inherently different as they do not have the same amount of testing points. Furthermore, not requiring the subjects to

respond to an FR1 may have influenced their response patterns at later FR conditions.

Though Raslear and his colleagues found in their second experiment that the order of FR presentation did not significantly influence consumption for the rats, different findings may have been found with pigeons whose first exposure was to an FR15.

Unfortunately, experimenter error required the removal of an entire subject's data. Pigeon 9's tube that connected the food magazine dispenser to the trough from which the subject received access was not properly connected after being sanitized during a procedural switchover. As such, the subject was responding to a lit response key but no reinforcers were being delivered. Though this did not completely extinguish the key pecking behavior, later experimental sessions were negatively impacted (total food consumption across all conditions was 284 pellets).

Pigeon 7's unusual FR45 datapoint could also possibly be explained by experimenter error. While the pigeon was being weighed to begin its FR45 condition, an identification bracelet attached to its ankle became hooked on the grate within its home cage. This caused the pigeon to behave erratically in an attempt to free itself. To ensure that the subject was spending as little time outside of its closed economy as possible, Pigeon 7 was still immediately returned to the experimental chamber like usual. The pigeons typically began responding during the beginning of each procedure (i.e., between 10:00 A.M. and 11:00 A.M.), but unlike the other subjects, Pigeon 7 remained stationary during this time. Though Pigeon 7 eventually began responding during that day's procedure, the adverse event likely caused the suppression in responding, and may have influenced its demand for later experimental conditions. Future replications with this

subject could help differentiate whether the potential outlier was due to error or was actually indicative of demand at that condition.

Future Directions

Fortunately, the convergent evidence between Raslear et al.'s (1988) study and the evidence presented here developed a strong foundation for future research to investigate. A general step towards providing verification of these findings would be to test for other cross-species similarities. For example, rhesus monkeys are commonly used in behavioral economic experiments; it would be beneficial to test these subjects using the same rapid demand procedure to see if similar outcomes are found. These studies should also aim to measure related variables, such as IRTs, PRPs, and circadian rhythmicity to make comparisons across experiments.

If future rapid demand research finds further evidence for cross-species similarities, it may be that there is some inherent demand process that leads organisms to behave how they do when presented with differentially costly circumstances. For example, a risk-reward paradigm could help explain demand behavior when operating within a closed economy. Ito, Takatsuru, and Saeki (2000) performed choice behavior experiments with Wistar rats within a closed economy. The rats responded under chained VI-FI schedules of reinforcement which lead to either a constant/guaranteed amount of food pellets or a variable amount of food pellets. When the rats were under a negative energy budget (i.e., their body weight was below 80% of free feeding), they were more risk-prone, choosing the variable food source which potentially provided more food. The effect of a closed economy may have influenced the subjects response patterns due to the restriction of access to food.

Similar research by Caraco, Martindale, and Whittam (1980) discussed how non-human animals often have differing response patterns in relation to the amount of time between access to reinforcers. They conducted a series of experiments where junco birds were able to obtain food from two equidistant sources (one which always guaranteed a single seed and the other which had a 50% chance of containing either 2 seeds or no seeds). Caraco et al. found that when trials were temporally closer together, the subjects avoided taking risks and went to the source with guaranteed food; when an expectation that food is available forms, why take risks? In contrast, when trials were temporally further apart, the subjects were more risk-prone, as the value of receiving 2 seeds likely outweighed the cost of receiving nothing at all when it came to survival. The findings from both Ito et al.'s (2000) and Caraco et al.'s (1980) experiments may explain why animal subjects are willing to respond at large FR values just to receive access to single food reinforcers. Resource allocation (e.g., pigeons spending energy to peck response keys) may be different if expectations about food consumption have formed, where uncertainty or restriction may increase the value of a commodity. The differences in demand patterns between the current experiment's pigeons who broke the closed economy and those who did not may be indicative of these expectations or differentiations in value. Fortunately, other behavioral economic principles, such as scarcity or delay discounting, could be studied in unison with demand and risk-taking behavior to form a more complete picture about what may be underlying these processes.

As Hursh (1980) emphasized, many other factors, such as the type of commodity or the availability of other reinforcers, can influence demand. Future experiments should examine how patterns of demand might change when altering these factors under rapid

conditions. For example, water, a primary reinforcer like food, would theoretically hold high demand and remain inelastic as it is a biological necessity. Demand curves could be generated for non-human animal subjects working for water, or even for both food and water presented simultaneously. Similarly, demand curves could be determined for secondary reinforcers, such as tokens, and be presented concurrently or separately from primary reinforcers. Furthermore, demand researchers should control for (or at least acknowledge) whether experiments are being performed under a closed or open economic system. Combinations of many of these manipulations (e.g., food vs. water presented under different schedules of reinforcement) could be used together through Raslear et al.'s (1988) rapid procedure to see how demand may change for any individual subject.

Conclusion

Overall, the use of Raslear et al.'s (1988) rapid demand procedure to determine a demand function was supported. A week-long procedure was inadvertently shortened to a 5-day procedure in the current experiment, potentially influencing demand outcomes as well as comparability across experiments. However, demand curves, evidencing clear decreases in consumption as price increased, were still able to be created for all subjects with moderate to strong model fits. These demand curves were similar to behavioral economic demand curves formed using both rapid and non-rapid experimental methods. Similarly, demand behavior produced by pigeon subjects related to that of rats, supporting potential cross-species similarities. This evidence may be suggestive of an underlying mechanism that organisms share in regard to the concepts of price and consumption. Parameter estimates for these demand functions were also determined,

which allowed for more distinct interpretations of different subjects' demand for (and valuation of) food reinforcers. Further research should attempt to replicate these findings with other species operating under speeded conditions in order to determine the value of different reinforcers.

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Table 1

Descriptive Statistics for Consumption across FR Conditions

FR Condition	<i>M</i>	<i>SD</i>
FR15	2004.83	518.13
FR45	486.64	556.25
FR90	179.59	159.45
FR180	36.23	21.51
FR360	15.81	16.57

Table 2

Repeated Measures ANOVA for Consumption across FR Conditions

Source	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>p</i>
FR Schedule	14034589.40	4	3508647.34	32.06	<.001
Error	1751201.92	16	218778.71		

Table 3

Exponential Demand Equation Parameter Estimates by Subject

Subject	α	k	Q_0	P_{max}	95% C.I. α	95% C.I. Q_0	R^2
Pigeon 1	0.000038	2.5	207	27.4	0.00018, 0.00025	2356, 2771	0.63
Pigeon 3	0.0000014	2.5	7970	19.31	0.0000008, 0.000002	754, 15185	0.99
Pigeon 5	0.0000017	2.5	3339	37.96	0.00000054, 0.0000028	-1502, 8181	0.96
Pigeon 7	0.0000072	2.5	665	45	0.000012, 0.000026	-3093, 4422	0.63
Pigeon 8	0.000004	2.5	3786	14.23	0.00000033, .00000078	-3885, 10457	0.93

Note. Average $R^2 = 0.83$. $k = 2.5$ for all subject as it is a constant in the exponential demand equation based off a range of logarithmic consumption values.

Table 4

Rapid Demand Measures by Subject

		Consumption	Total Responses	DTR	DIRT	DPRP	NTR	NIRT	NPRP	Weight (g)
Pigeon 1	FR15	2428	36420	36221	4.22	9.38	199	220.53	29.5	492
	FR45	86	3873	3873	60.55	212.27	0	---	---	453
	FR90	12	1116	1116	359.16	89.73	0	---	---	436
	FR180	4	742	742	453.38	1289.8	0	---	---	431
	FR360	0	248	248	1498.33	---	0	---	---	427
Pigeon 3	FR15	2655	39827	39790	5.6	5.14	37	991.1	2.8	521
	FR45	1137	51165	44865	5.84	44.1	6300	7550.9	6	550
	FR90	160	14400	12242	21.81	93.11	2158	389.5	7.3	499
	FR180	54	9722	6298	53.81	199.32	3424	319.52	12.5	484
	FR360	30	10890	9108	44.71	20.66	1782	188.47	28	470
Pigeon 5	FR15	1670	25050	24784	9.89	9.27	266	10915.4	60.9	481
	FR45	1050	47250	32310	3.53	47.11	14940	1064.87	9.4	482
	FR90	391	35213	20003	5.11	157.62	15210	453.08	20.3	445
	FR180	58	10446	6486	24.01	782.28	3960	386.01	25.7	431
	FR360	36	13270	9827	27.99	522.98	3443	99.28	0.02	417
Pigeon 7	FR15	1427	21405	21405	3.25	47.7	0	---	---	410
	FR45	24	1083	1083	111.24	357.45	0	---	---	432
	FR90	286	25740	24736	11.17	34.77	1004	11.32	6.2	438
	FR180	32	5760	5755	31.35	568.36	5	71590.5	---	438
	FR360	4	1697	1678	220.24	41	19	17914.4	---	426
Pigeon 8	FR15	1844	27660	27150	6.69	16.7	510	24.1	24.7	507
	FR45	136	6123	5583	40.18	323.36	540	4480.21	20.4	475
	FR90	48	4346	4294	62.11	344.9	52	8428.95	3045.8	466
	FR180	32	5934	5862	60.34	230.1	72	6027.54	---	462
	FR360	7	2599	2574	157.9	83.6	25	17077	---	460

Note. DTR = Daytime Responses, DIRT = Daytime Interresponse Time (s), DPRP = Daytime Post-Reinforcement Pause (s), NTR = Nighttime Responses, NIRT = Nighttime Interresponse Time (s), NPRP = Nighttime Post-Reinforcement Pause (s).

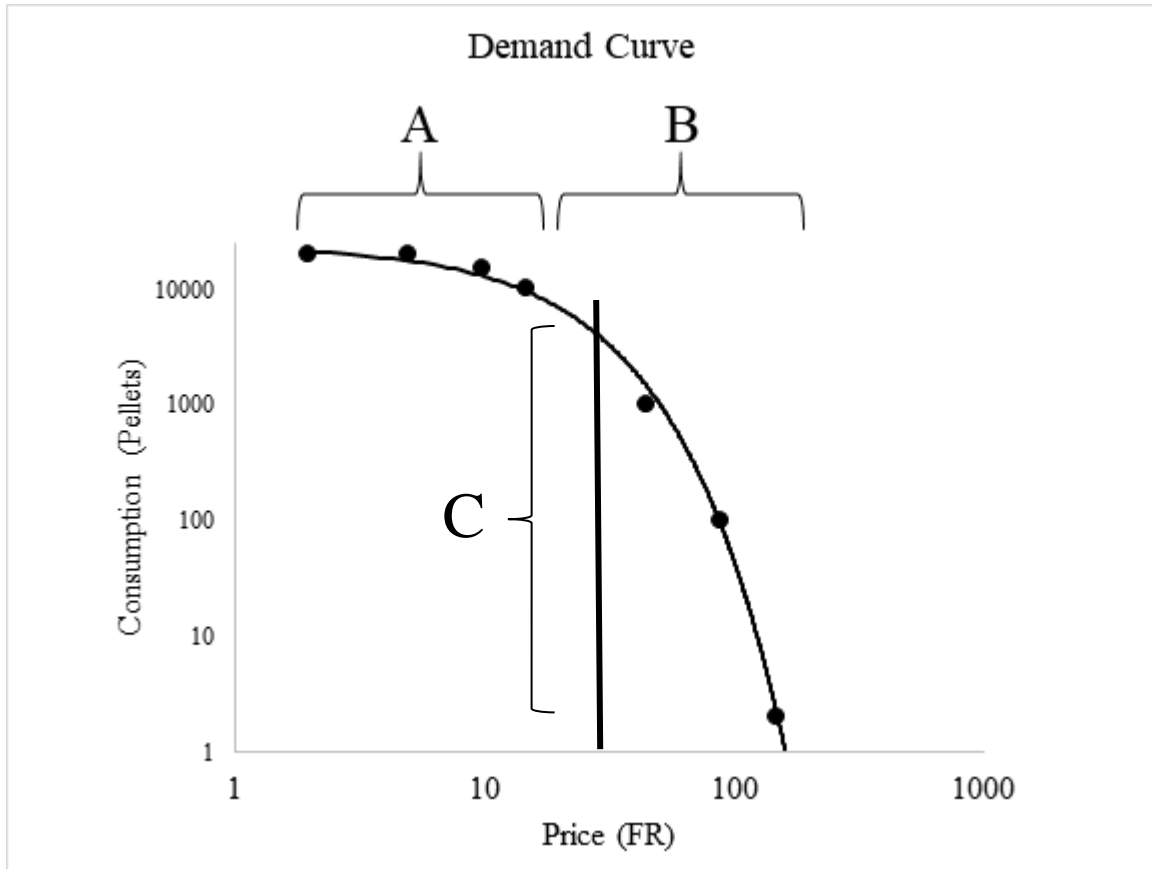


Figure 1. Representation of a typical demand curve in experimental settings.

Inelastic demand occurs at section A, where changes in price produce relatively small changes in consumption. Elastic demand occurs at section B, where changes in price produce relatively large changes in consumption. The point at which demand elasticity becomes more negative than -1 is represented by the vertical line C.

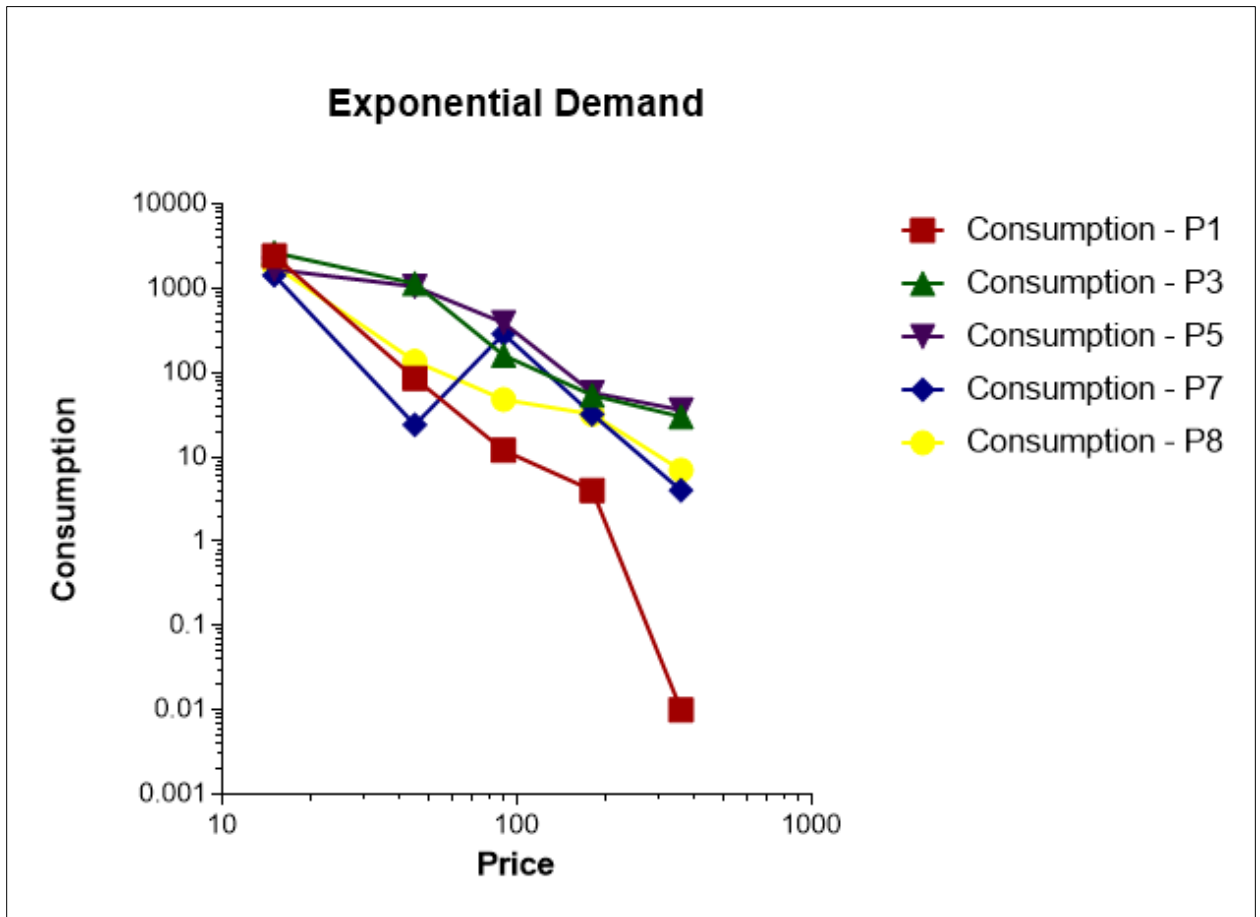


Figure 2. Demand curves representing the exponential demand function for each animal subject. Both axes are scaled logarithmically.

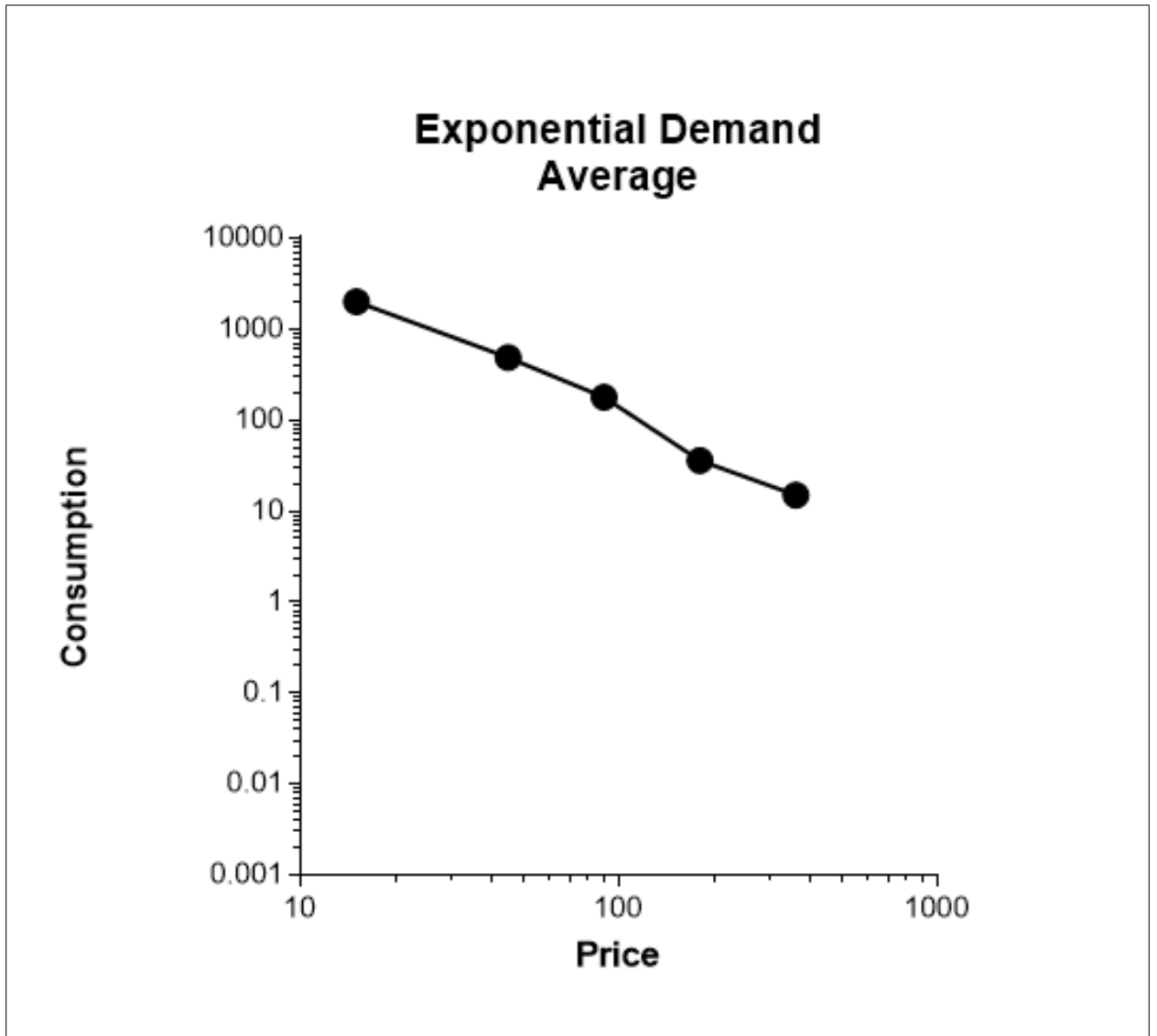


Figure 3. Demand curve representing the average exponential demand function across animal subjects. Both axes are scaled logarithmically.