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David L. Dickinson
Appalachian State University, IZA and ESI

Ananish Chaudhuri
University of Auckland

Ryan Greenaway-McGrevy
University of Auckland

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ABSTRACT

Trading While Sleepy? Circadian Mismatch and Excess Volatility in a Global Experimental Asset Market

Traders in global markets operate at different local times-of-day. Suboptimal times-of-day may produce sleepiness due to daily variations in sleep/wake patterns and possibly also increased accumulation of hours awake. Global asset markets imply significantly increased heterogeneity in circadian timing, and likely sleepiness, of trader decisions compared to localized markets. We examine these factors by administering single-location and global sessions of an online asset market experiment that regularly produces valuation bubble and crash events. Global sessions involved real time trades between subjects in two locations 16 time zones apart (i.e., "global" markets) and at varied local times of day across sessions. We find asset market bubbles occur in all sessions, but global markets had significantly more extreme and longer duration valuation bubbles. Additionally, subjects at the most suboptimal times-of-day held significantly more asset shares in their portfolios in late trading rounds compared to other subjects – a risky strategy with overvalued shares. Overall, our results highlight a unique but underappreciated factor present across traders in global market environments. They also point to the importance of a relatively common cognitive state (i.e., suboptimal time-of-day) in attempting to understand trader behavior and, ultimately, market outcomes.

JEL Classification: C92, G12, G15, D84
Keywords: asset markets, experiments, bubbles, sleep, circadian rhythm

Corresponding author:
David Dickinson
Walker College of Business
3090 Peacock Hall
Boone, NC 28608-2037
USA

Email: dickinsondl@appstate.edu

1. INTRODUCTION

Globalization, along with its impact on diverse aspects of our lives, has also led to the creation of global financial markets (e.g., markets for foreign exchange, treasuries and commodities to name a few), that involve traders who are physically located in distant geographic locations. It has now become common-place for a trader located in Auckland, New Zealand to trade in markets located in London, New York or Tokyo. However, this raises an often under-appreciated issue that has implications for the degree of volatility of such markets, which will likely become more prominent with increasing globalization and improving technology.

This issue refers to the fact that participants in such markets are often making important decisions, with substantial financial implications, at significantly different local times-of-day. Previous research has identified "circadian desynchronosis" as a cause of the negative effect of daylight savings time (DST) changes on stock returns, highlighting that even small circadian shocks may have significant and meaningful impacts. (Kamstra, Kramer and Levi, 2000).

Decisions at 3:00am (the "witching hour"), for example, are made during a time of when sleepiness is relatively higher than at other times due to natural circadian variations in melatonin production. Such late night (or early morning) decision times might also be impacted by accumulated hours awake, which are particularly high late at night and further contribute to sleepiness. Because of the heterogeneity in the circadian timing of decisions among participants in global real-time markets, those trading at more suboptimal local times of day may be at a particular disadvantage when high level thinking and anticipation are critical skills.

We study a commonly used (and well-validated) experimental asset market environment to examine asset pricing and trader decisions. We show that circadian mismatch among the traders involved in such markets significantly increases market volatility. This paper is the first, to our knowledge, to systematically examine the impact of globalization (and the consequent "circadian desynchronosis" among traders) in such global asset markets. We proceed as follows, In Section 2, we provide a brief overview of the related literature. In Section 3, we present our hypotheses, which is followed by a description of our experimental design in Section 4. We present our results in Section 5. Finally, in Section 6 we make some concluding remarks, where we also explore some avenues for further research.

2. LITERATURE REVIEW

In general, unimpaired cognition would seem to be necessary for successful asset market performance. This would implicate one's ability to engage prefrontal regions that are important in high-level executive function (in addition to one's permanent level of cognitive ability). Deliberative thought may also be important for limiting the influence of cognitive bias in such decision environments, such as trader overconfidence.

Evidence shows that those scoring higher at Theory of Mind (ToM) exhibit increased medial Prefrontal Cortex Activation (mPFC) and are better at predicting prices in asset markets with insiders (Bruguier et al, 2010). Relatedly, researchers have found that mentalizing during strategic interactions (Hampton et al, 2010) invokes regions of the brain known to be impacted by sleep deprivation (Yoo et al, 2007). Though brain regions implicated in ToM appear to be distinct from those involved in mathematical calculations, the prefrontal cortex, more generally, is known to be particularly vulnerable to sleep loss (e.g., Horne, 1993; Chee and Chua, 2008). Researchers have concluded that successful anticipation involves the higher levels of cognitive reasoning implicated in ToM (Coricelli and Nagel, 2009). Others report that both analytical and mentalizing dimensions of cognition are required for successful trading behavior (Heft et al, 2016).[1]

[1] A recent paper by Corgnet et al (2015) also concludes that standard cognitive skills are not necessarily what make traders successful, but rather display of behavioral biases such as overconfidence may be a stronger indicator of poor performance in asset markets. However, they also conclude that ToM skills have only a marginal effect, which is different than what others have concluded (e.g., Bruguier et al, 2010).

A different strand of research has examined the importance of behavioral biases, such as overconfidence, on trader performance. For example, Michailova (2011) finds that overconfidence leads to larger price bubbles and such overconfidence is larger in the latter half of the 15-round asset market (see also Kirchler and Maciejovsky, 2002). Scheinkman and Xiong (2003) offer a theoretical argument based on the idea that traders may be willing to pay more than their expectation of an asset's future dividend value as long as it is believed another trader in the future will be willing to pay even more.[2]

The connections between mentalizing (ToM), overconfidence, and asset market behavior are important given the results in the sleep literature. Specifically, neuroscience has shown that sleep loss disproportionately impacts prefrontal and executive function brain regions (Horne, 1993; Muzur et al, 2002; Chee and Chuah, 2008), and behavioral research has shown that anticipation of other's choices can be harmed even at relatively mild off-peak times of day (Dickinson and McElroy, 2012). Furthermore, sleep researchers have found a recent neural basis for claiming that mild sleep restriction may increase optimism by accentuating the brain's focus on positive reward anticipation (Venkatraman et al, 2011).[3] In a recent paper, Castillo et al (2017) also showed that subjects at suboptimal times of day chose riskier asset bundles in an individual decision making risky choice experiment. Together, the research implies that sleepiness, in a general sense, has been implicated in reduced capacity to anticipate and an increased potential for

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[2] Others have found that overconfidence in equity trading data may result in higher frequency trading activity (Grinblatt and Keloharju, 2009).

[3] More specifically, to the extent that sleep deprivation may selectively *increase* activation in portions of the prefrontal cortex (i.e., the ventro-medial PFC), the evidence suggests that such increased activation represents the decision maker's increased focus on monetary gains potential. In other words, in the context of our task where monetary gains and losses are at stake, the increased PFC activation that may result from sleepy traders is of the type that would suggest an increased optimism bias as opposed to an increase in likely decision quality (see Venkatraman et al, 2007, 2009, 2011)

optimism in decision making. Both of these sleep effects are hypothesized to be present to some extent in asset markets with natural heterogeneity in trader alertness due to the global nature of the market.

3. HYPOTHESES

The background research summarized above supports a set of hypotheses regarding outcomes in our global asset markets. Specifically, research shows that mentalizing skills (i.e., one's ability to anticipate) would be compromised and overconfidence enhanced at suboptimal times-of-day. This is important because both of these behavioral effects are predicted to increase asset market bubbles and our global experimental markets (henceforth, "Global Markets") create a type of natural experiment with respect to heterogeneity in alertness across traders. This leads to our first hypothesis, which focuses on aggregate market level outcomes.

Hypothesis 1: Global Markets will produce more significant asset market bubbles.

Our second hypothesis focuses on individual trader behavior. A premise of our hypotheses is the fact that suboptimal times of day are predicted to increase preference for riskier asset bundles (i.e., more shares over cash) and reduce a trader's ability to anticipate others' actions (e.g., hold shares while others are selling). Relatedly, the aforementioned research highlight the potential for increased optimism regarding favorable monetary outcomes, and so traders at suboptimal times of day may wish to hold more assets in anticipation of favorable dividend draws or resale prices.

Hypothesis 2: Traders at more suboptimal times of day will hold more shares (the riskier asset) or, more specifically, hold more shares in later trading rounds.

Because our markets fix the total number of shares available for trading, our ability to assess difference in portfolio holdings within a market must focus on Global Markets that induce heterogeneity in how suboptimal the local time-of-day is for different traders (see also

Baghestanian et al, 2015 on the importance of trader heterogeneity in understanding asset market bubbles). In other words, data on share holdings across rounds in a Local market session at 4 am would not allow for a test of a hypothesis focused on differences in sleepiness from different local times-of-day. In such a market, all subjects would be at a similar suboptimal time of day and so shares sold by one sleepy trader are, by necessity, purchased by another sleepy trader. Thus, heterogeneity in local times of day *within* a session is required to test a hypothesis regarding share holdings in our particular environment. Given the aforementioned evidence that sleepy traders prefer riskier assets, have reduced anticipation skills, and increased overconfidence, our Hypothesis 2 stems from the fact that it is inherently more riskier in our design to hold asset shares in later trading rounds given the ultimate redemption of shares at fundamental value implies market bubbles eventually crash.

While increased risk taking need not imply lower asset market earnings, we will explore earnings differences across trader types. Reduced mentalizing or increased overconfidence favor poorer decisions that may be exploited by alert traders and result in lower earnings. Increased risk taking, per se, may or may not impact average trader earnings, and so differences in earnings in our design may reflect more on the impact circadian timing has on anticipation or overconfidence. Lower earnings of sleepy traders is at least indirect evidence that circadian suboptimal timing impacts the quality of trader decisions. We highlight this as our third hypothesis:

Hypothesis 3: Sleepy traders will earn less due in global markets.

4. EXPERIMENTAL DESIGN

The limit-order asset market environment we implement is based on the constant (flat) fundamental asset value design of Bostian et al (2005) and Bostian and Holt (2009). Groups of 7-

13 subjects (median group size = 11 subjects) participated in the online asset market experiment. Participants were not asked to come in to a lab and once signed up could participate from any location of their choice, likely their homes. Subjects were recruited for a 2 hour online experiments that required them to get online at specific local time-of-day on the day of the session, and they were paid a fixed payment that varied depending on the local time of day of the session (see note to **Table 1**).[4] Sessions were scheduled so that all subjects participated on either a Tuesday, Wednesday, Thursday (no matter which location) to avoid weekend sleep effects as much as possible.

Subjects were instructed that, at the session start time, the experimenter would email them a link to a short (5 minute) online survey to collect demographic, self-report sleep data, and a (validated) measure of "morningness" or "eveningness" preferences (Adan and Almirall, 1991). Additionally, the online survey was used to elicit self-reported sleepiness as a way to validate our methodology. The experimenter monitored survey responses in real time to verify the number of subjects who had got on-line, and this final group size was then used to configure the asset market experiment.[5]

Experiments were conducted through Veconlab's limit-order asset market experiment option[6] and the subjects were told that they would be emailed the login credentials for the main market experiment shortly after completion of the online sleepiness survey. Within the asset market experiment, the experimenter could utilize a message board embedded in the program to post messages to subjects individually or as a group (e.g., "30 seconds until the round ends, please

[4] Rates of subjects who signed up but were not online for the experiment (i.e., virtual no-shows) were as follows: 4am—20%; 8am—12.5%; noon—15.6%; 4pm—20%; 8pm—16%; midnight—24%.

[5] The experimenter conducted the experiments online and was in the same time zone as the east coast US subjects.

[6] The various experiment options for the *Veconlab* Internet-based platform for experiments can be accessed at http://veconlab.econ.virginia.edu/admin.htm . The specific experiment used is the "Limit Order Market" option under the "Asset Market" submenu of the "Finance/Macro" experiment section.

make your final decisions for this round"). However, the experimenter continued to monitor his email in the event a subject sent a clarification question because subjects could not utilize the market message board. Subject questions to the experimenter were, however, minimal given the Veconlab instructional pages included comprehension verification questions prior to allowing the subject to enter the first market decision round.

In the experimental asset market, subjects were endowed with $50 of experimental cash and 6 shares of the experimental asset. Two treatments varied the asset returns in a way that preserved a constant fundamental asset value of $7 in all round of all treatments. Specifically, in the *Low Returns* treatment, cash held at the end of each round received 10% interest, and in each round, shares earned a dividend of either $.40 or $1.00 (so, the expected dividend was $.70 per round in Low Returns) and shares were redeemed for $7.00 at the end of the final period of the treatment. As such, the fundamental share value was $.70/.10 = $7.00. In the *High Returns* treatment, cash paid 20% interest but the dividend draw on shares in each round was either $1.10 or $1.70, or a $1.40 expected dividend draw in each round. Consequently, *High Returns* infused more cash into the market, but the fundamental share value was still $1.40/.20 = $7.00 per share in each round.

A session lasted for 30 rounds, with 15 rounds in each treatment, *High* or *Low Returns*. The order was counter-balanced across sessions. Experimental earnings were paid at a rate of $100 experimental dollars = US $1. Subject payments were arranged within 24 hours of the session completion. In New Zealand, subjects were given the opportunity to receive their cash payment (in equivalent NZ dollars corresponding to US earnings[7]) as soon as the day after the experiment. The U.S. subjects were paid their earnings through PayPal with 24 hours of the end of the session.

[7] At the time the experiments were carried out in August 2015, the exchange rate was roughly US $1 = NZ $1.38.

Average asset market earnings were US $18.92 (median $18.69), which did not include the guaranteed fixed compensation of an additional $10, $20, or $30 depending on the local time of day of the experiment sessions (see Note to **Table 1**)

Eight of our sessions involved traders in a single geographic location (East Coast, USA, or Auckland, New Zealand), while the other 12 sessions involved markets populated with traders in both of these locations, which were 16 time zones apart at the time of the experiment sessions (see **Figure 1** and **Table 1**). We label single-location markets as "Local Markets" while real-time trading with participants in both locations are what we call "Global Markets". Notably, traders were not aware of other traders' location and therefore had no idea others might be in a different country (market interactions were all online). Sessions took place at local times of 12pm, 4pm, 8pm, 12am, 4am, and 8am at each location (see **Table 1**), and decisions were incentivized with payoffs that were a function of experimental earnings.

<<Figure 1 about here>>

<<Table 1 about here>>

It is important that there is heterogeneity in the optimality of the local session time-of-day across subjects. Recall, the pre-experiment survey administers a validated short-form morningness-eveningness questionnaire. Evening-type subjects will generally possess a phase delay of roughly two hours relative to morning-type subjects in terms of their optimal alertness time-of-day. Smith et al (2002) highlight the diurnal pattern of self-reported alertness ratings for individuals of different diurnal preferences types. We adapt their methodology in **Figure 2** with a normalized scale describing the level of sub-optimality of the local time of day, which we call mismatch level, or "MMlevel" $\in [0,1]$. The colored bands indicate *high (red), medium (yellow), and low (green)* predicted *mismatch (MM)* levels, and we later dichotomous this as *HighMM=1* for high (red band) mismatch levels in **Figure 2**. As can be seen in **Figure 2**, the more significant difference between predicted alertness is between those within the red band (e.g., anyone at 4am, evening-types at 8am) compared to others. This methodology will allow us to create a categorical variable describing those at high level of "circadian mismatch" during the local time-of-day of the asset market to others. Our efforts in scoring such a variable using a validated diurnal preference measure and research-based alertness patterns reflects the focus of our study on the importance of time-of-day heterogeneity in our Global Markets.

<<Figure 2 about here>>

5. RESULTS

Result 1: Global asset markets exhibit more significant bubbles.

Figure 3 shows market trading prices across the 15 rounds of the low returns treatment. Panel A shows prices for local markets while Panel B does so for global markets. **Figure 4** presents the corresponding information for local (Panel A) and global markets (Panel B) for the high returns treatment. The think black line represents the average market price across all sessions shown in the same plot. Two things are apparent from **Figures 3 and 4**. First, shares are over-valued in most rounds in all sessions. Second, while asset bubbles occur in all markets, the most extreme bubbles seem to occur in global markets.

<<Figure 3 about here>>

<<Figure 4 about here>>

In order to test for excess volatility in global markets, we compare between local and global market using the following bubble measures. (1) *Maximum Price:* the maximum market clearing share price in the market (across all rounds); (2) *Duration:* the longest run of market price increases across consecutive rounds; (3) *Normalized average price deviation (NAV):* the sum of the absolute deviations of market price from fundamental share value for each trading round and (4) *Turnover:* transaction volume across all trading rounds relative to total available shares (see Corgnet et al, 2014). In **Table 2**, we present an overview of these measures along with Mann-Whitney nonparametric test statistics for the differences in means. We treat the average for each session as an independent observation. The reliance on 1-tailed tests is justified given our *ex ante* hypothesis of greater volatility in global markets.

While not all measures show significant differences across treatments, we find considerable evidence in support of larger bubbles in global markets, consistent with Hypothesis 1. Other than *Turnover*, the means for the other three bubble measures are consistently higher for global markets compared to local markets. The bubble measure for which we find the most robust difference is *Bubble Duration*. Bubbles are significantly longer lasting in global markets in both the high returns ($z = 1.705$; $p = 0.04$) as well as low returns ($z = 1.713$; $p = 0.04$) treatments. *Maximum Price* is significantly higher global markets in the high returns treatment ($z = 1.481$; $p = 0.07$). Finally, *NAV* is significantly higher in global markets in the low returns treatment ($z = 1.312$; $p = 0.09$) while it narrowly misses conventional significance levels in the high returns treatment ($z = 1.099$; $p = 0.14$). Thus, at the session level we find support for Hypothesis 1 with respect to a number of measures of asset market volatility.

Result 2: Traders at more off-peak times of day hold riskier asset portfolios.

This result relates to the second of our hypotheses stated above. Here we are going beyond aggregate measures of market volatility to look at individual level decisions that may contribute to such volatility. We start by looking at average share holdings at different points in the market's (commonly known) 15-period life for subjects who are likely to be at a circadian suboptimal time of day as opposed to those who are not. This classification is done on the basis of the alertness profiles one would predict for subjects with different diurnal preferences at different times-of-day, as depicted in **Figure 2**. For example, the most suboptimal time in our data set (e.g., anyone trading at a 4:00 am local time-of-day, as well as evening-types at 8:00 am or morning types at midnight), we consider as highly circadian mismatched. This allows us to code a binary variable *HighMM*=1 for those who are highly mismatched and *HighMM*=0 for the rest. Below, for the ease of exposition, we will often refer to the *HighMM=1* traders as "*tired*" or "*sleepy*" and the *HighMM=0* traders as "*alert*".

This approach ignores any compensatory behaviors of the subject to combat sleepiness, which is not part of our data set. While this may seem a limitation in our data, we document the validity of this approach using self-reported sleepiness ratings (1=lowest, 9=highest sleepiness rating on what is called the Karolinska sleepiness scale) elicited in the online survey administered immediately prior to asset market trading experiment. Using data from all of our 20 experimental sessions (n=206 total subjects), we report a significantly higher self-reported sleepiness among HighMM=1 subjects (n=51, Karolinska sleepiness =5.91) compared to the *HighMM*=0 subjects (n=156, Karolinska sleepiness=4.87) using the nonparametric Mann-Whitney two-sample test of means (z-stat = -3.543; p <0.01).

Our global markets are those with the most intra-market heterogeneity in circadian mismatch level due to the different local times of day for the traders in those markets. This heterogeneity does not necessarily exist in local markets, which may even contain subjects of a singular type (e.g., a local market at noon may be comprised of only *alert (HighMM*=0) subjects, while a local market at 4:00 am will likely have only *tired* (*HighMM*=1) subjects). Next, we analyze differences in average share holdings of subjects in each round of a given treatment. We use data from global markets only for reasons adduced above. Recall that in our experimental asset market, there is a fixed number of shares (6 per subjects) initial allocation and no new shares are generated (nor shares destroyed) during the trading rounds. Because of this, average share holdings in Local Markets will always be 6 shares per subject in any trading round. While this is true for global markets, the heterogeneity of circadian mismatch in such markets may lead to tired subjects having different average share holdings than alert subjects. Local sessions that may not have adequate heterogeneity in the levels of tiredness/alertness will mask this effect of interest--to examine whether tired subjects tend to have different share-holding patterns than alert subjects—particularly if tired subjects tend to hold shares (the risky asset) deeper into the game.

Figure 5 shows average share holdings of subjects for tired and alert subjects pooled across sessions for a given round and treatment in global markets. Not only are shares riskier than cash in this market experiment, but shares held late into the game are riskier than at other times in the life of the market. We divide up the 15 rounds in each treatment (low or high returns) into **early rounds (Rounds 1-8)** and ***late rounds (Rounds 9-15)***. The two panels of Figure 5 separate the low returns treatment (Panel A) from the high returns (Panel B) treatment. It is clear that tired subjects hold more shares on average in the late rounds compared to the early rounds.

<<Figure 5 about here>>

The data underlying **Figure 5,** are shown in **Table 3**. It is apparent, both from **Figure 5** and **Table 3**, that tired subjects hold more shares in later trading rounds than alert subjects, which is a riskier portfolio in general (compared to safer cash available in the experiment, which earns a certain interest rate). T-tests document significant differences in share-holdings of tired/alert subjects when comparing share-holdings in early rounds (Rounds 1-8) versus late rounds (9-15).

<<Table 3 about here>>

Table 4 presents results from random effects regressions for share-holding patterns.[8] The results are presented separately for treatment: high or low returns. In each case, we present two specifications for the set of independent variables. The parsimonious specification includes a dummy *HighMM* (HighMM=1 if tired; 0 otherwise), another dummy for *LateRound* (=1 if Round>8; 0 otherwise), an interaction term between the *HighMM* and *LateRound* dummies and a constant. The alternative specification adds the following variables to the ones in the first specification: *Female* (=1 for female subjects; 0 for males); *MathGood* (high math level implies *MathGood*=1; 0 otherwise); *Epworth* (daytime sleepiness scores; higher scores indicating greater sleepiness); *PerSD* (self-reported levels of personal sleep deprivation over the previous week; higher scores indicate greater sleep deprivations) and *Experience* (whether the trader is in first or second half of the session and has, therefore, already experienced an asset market and bubble phenomenon.[9]

The results in **Table 4** corroborate the findings reported in **Table 3** and **Figure 5**. First, suboptimal time-of-day traders hold more shares in later rounds compared to other traders. To see this, first note that the average number of shares held late in the game by an alert (i.e., more preferred time-of-day) trader is given by *constant* + *LateRound*, whereas the average number of shares held late in the game by a sleepy (i.e., more suboptimal time-of-day) trader is *constant* + *LateRound* + *HighMM* + *HighMM*LateRound*. Thus if *HighMM* + *HighMM*LateRound* is significantly greater than zero (in a one-tailed test), tired subjects hold more shares than alert subjects in later rounds. In all model specifications, *HighMM* + *HighMM*LateRound* is positive,

[8] As a robustness check, we also run random effects with errors clustered at the level of sessions given the non-independence of observations within a session. The results are similar except the levels of significance are at times less than the ones without clustering.

[9] The scoring of *MathGood*=1 accounted for differences in the average math levels of New Zealand versus U.S. student. Specifically, we asked subjects to self-report their grade in the last high school math course they took. Taking into account the different grading standards, we scored about 45% of the U.S. subjects (n=125 total) as *MathGood*=1 and about 56% of the New Zealand subjects (n=82 total) as *MathGood*=1.

and the Wald test on the linear restriction *HighMM + HighMM*LateRound = 0* can be rejected at a 5% level for the high returns treatment, and marginally rejected in the low returns treatment (one-tailed significance at **5% or better** is shown in **bold**, while significance at *10% or better* is *italicized*).

Second, the suboptimal time-of-day traders increase their shareholdings between early and late rounds. To see this, first note that the average number of shares held early in the game by a sleepy trader is given by *constant + HighMM*, whereas the average number of shares held late in the game by a sleepy trader is *constant + LateRound + HighMM + HighMM*LateRound*. Thus if *LateRound + HighMM*LateRound* is significantly greater than zero, tired subjects increase their shareholdings on average between early and late rounds. This also supports Hypothesis 2. In all model specifications, *LateRound + HighMM*LateRound* is positive, and the Wald test on the linear restriction *LateRound + HighMM*LateRound* = 0 can be rejected at a 5% level.[10]

In **Table 5**, we report results of random effects regressions for average individual price bias, an alternative measure of individual level variation in trader behavior, where ***Average individual bias*** $= QBid_t*(BidPrice_t - Price_{t-1}) + QAsk_t*(AskPrice_t - Price_t)$. We undertake the same comparisons as made in **Table 4**. First, in all model specifications, *HighMM + HighMM*LateRound* is positive, and the Wald test on the linear restriction *HighMM + HighMM*LateRound* = 0 can be rejected at the 1% level for the high returns treatment (the test-statistics are insignificant at conventional levels for the low returns treatment). This suggests that tired traders exhibit more price bias in later rounds than alert traders – particularly in the high cash

[10] Unfortunately, we did not elicit beliefs from traders regarding expected dividend outcomes or asset prices, which would have helped to discriminate between the different potential mechanisms that could all contribute to tired subjects holding more shares in later rounds. For example, though tired subjects are predicted to be both more overconfident in holding shares and also less able to anticipate a market downturn, our data may not be sufficient to distinguish between these two mechanisms, although earnings analysis we conduct later in this section may help identify whether risk taking plays an important role independent of anticipation and overconfidence.

(returns) environment. Second, in all model specifications *LateRound* + *HighMM*LateRound* is positive, and the Wald test on the linear restriction *LateRound* + *HighMM*LateRound* = 0 can be rejected at the 1% level in the high returns treatment (again, the test-statistics are insignificant at conventional levels for the low returns treatment). This indicates that tired traders tend to increase their bid and offer prices as the game progresses (especially in the high cash environment).

Result 3: There are no significant differences in the earnings of tired and alert subjects.

In **Table 6**, we present random effects regressions for log earnings. The regressors are the same as those in **Tables 4 and 5**. Few of the variables are significant except for the female dummy indicating that female traders earned less than male traders. More importantly, we do not find that tired subjects are exploited by alert ones in terms of the former earning less than latter. While the coefficient for the relevant variable is negative in all specifications, its significance is nowhere near conventional levels. So, while circadian mismatch heterogeneity in traders leads to significantly increased market volatility, our data does not suggest that tired traders earn less than alert ones over the course of the entire market session.

The coefficient on *HighMM* in **Table 4** suggests that sleepy traders do not hold more shares than alert traders, and they marginally hold fewer shares in the Low Returns treatment. An asset portfolio with more shares, on average, would be evidence of increased preference for a riskier portfolio and we do not find evidence to support this general assertion. The weight of our evidence has shown that sleepy subjects hold shares across the course of the 15-round market in a way that suggests poor anticipation or overconfidence dominates the pure impact suboptimal circadian timing may have on trader risk preference. The lack of support for Hypothesis 3 is therefore somewhat surprising. Perhaps a longer-life market may give heterogeneous trader more time to exploit poor decisions in the market in a way that will manifest in earnings differences.

Future research may wish to more carefully explore the earnings implications of cognitive impairment in traders.

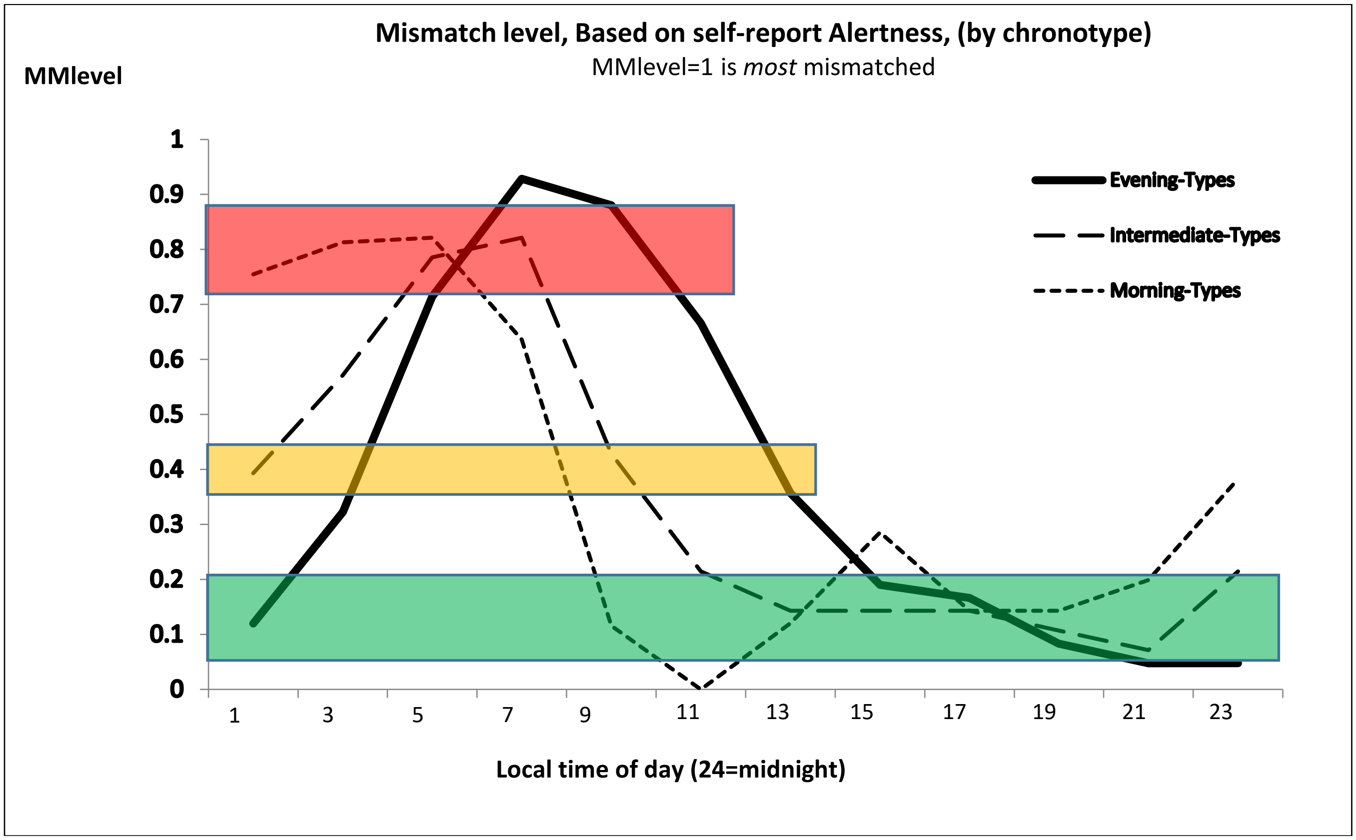
6. CONCLUSION

We explore an under-appreciated characteristic of global financial markets in the sense that some of the traders engaging in these markets are making decisions at sub-optimal times of day. This leads to significant circadian desynchronosis between traders, which may be an important heterogeneity in the cognition of traders in such global markets. At the aggregate level, we found that this heterogeneity in circadian mismatch of traders in our global experimental markets resulted in more pronounced asset price bubbles. At the individual level, we found that those trading at sub-optimal times-of-day tended to engage in different trading behaviors than those trading at more favorable times. The "tired" traders tended to hold shares (the risky asset) deeper into the market trading rounds and also exhibited a greater degree of price bias, in the sense that their bid and ask prices in any round were further away from the market price than in the previous round. These aggregate and individual-level trader results support our first two hypotheses. However, contrary to our third hypotheses, there seem to be no adverse ramifications in terms of earnings for tired traders in a global market. This may be due to two different factors. First, it is not prima facie obvious that riskier strategies will necessarily result in lower earnings, and some risky strategies may be hard to empirically distinguish from poor anticipation or other cognitive impairment. A different experimental design may be required of future research in order to more directly examine the cognitive underpinnings of the trader decisions and which components are most impacted when sleepy. It is also possible that the market duration (15 trading rounds) in our design was not long enough for alert subjects to take advantage of tired subjects in a way that shows up as meaningful differences in earnings.

To what extent are these results generalizable to real life global asset markets? Is it not the case that in actual markets those trading at sub-optimal times are self-selected and, therefore, better able to handle any potential circadian mismatch? We believe that these concerns are unfounded. For one thing, even among our subjects there was a degree of self-selection; subjects were free to choose their participation slots and it is likely that the ones who thought they could handle the odd time-of-day sessions signed up for those. This actually implies our results would be a conservative estimate of the true impact of suboptimal times-of-day on trading decisions (i.e., the traders at the most suboptimal times-of-day would be those who felt they could handle it best). The point here is that a measure of self-selection in our experimental subjects somewhat mimics a feature of naturally occurring field data on trader behavior. But more fundamentally we are making two points. First, the presence of circadian mismatch and heterogeneity in local times-of-day across traders will lead to greater market volatility. Second, those operating at sub-optimal times of day will engage in differential trading strategies that may involve increased risk taking or behaviors symptomatic of cognitive impairment. Even if the net impact on earnings across trader types is not significant (and we believe more research should be done to explore that possibility), increased volatility in markets should be enough to highlight the importance of our findings.

FIGURE 1: Participant Locations

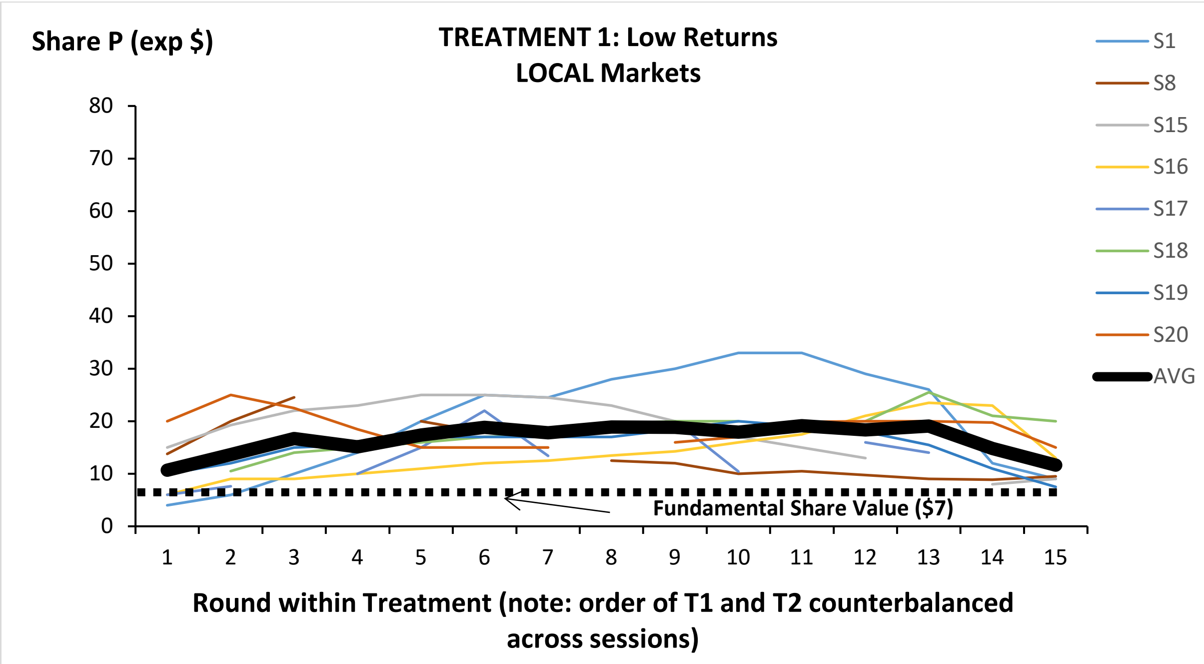
FIGURE 2: Guide for scoring of High Mismatch variable.
(colored bands represent the clusters of scored MMlevel in our data)



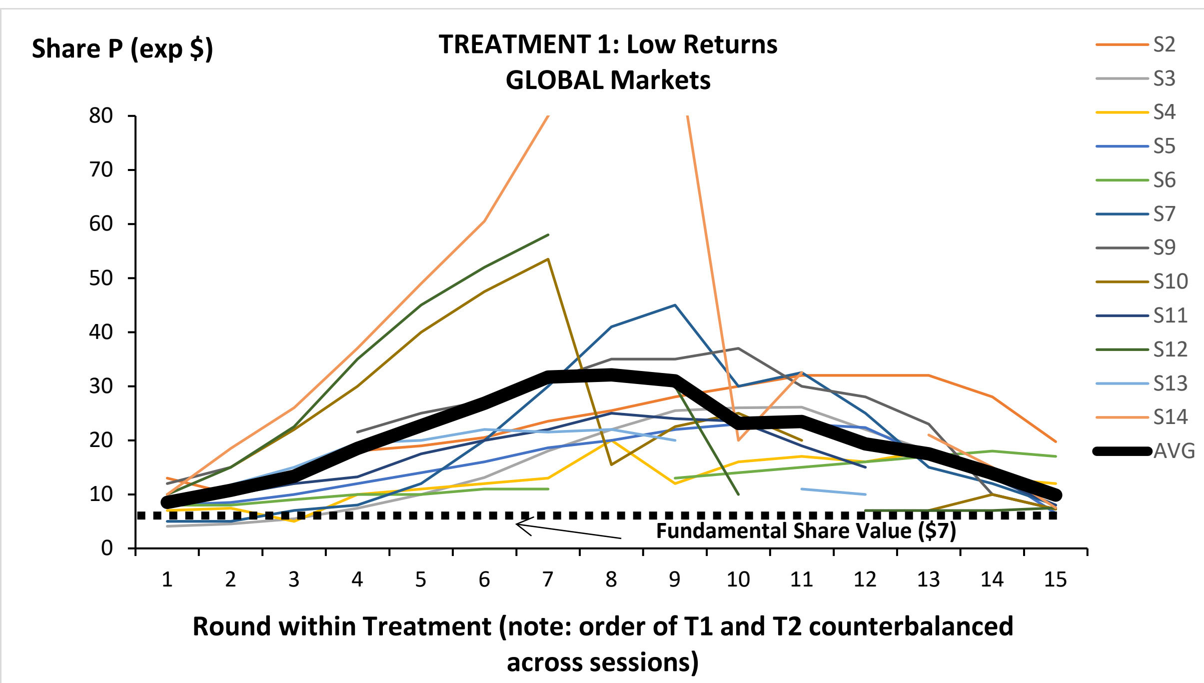
Note: Graph adapted from alertness levels in Fig 1 in Smith et al (2002)

FIGURE 3: Local vs. Global Markets: Prices across rounds in Low Returns Treatment

Panel A: Local Markets



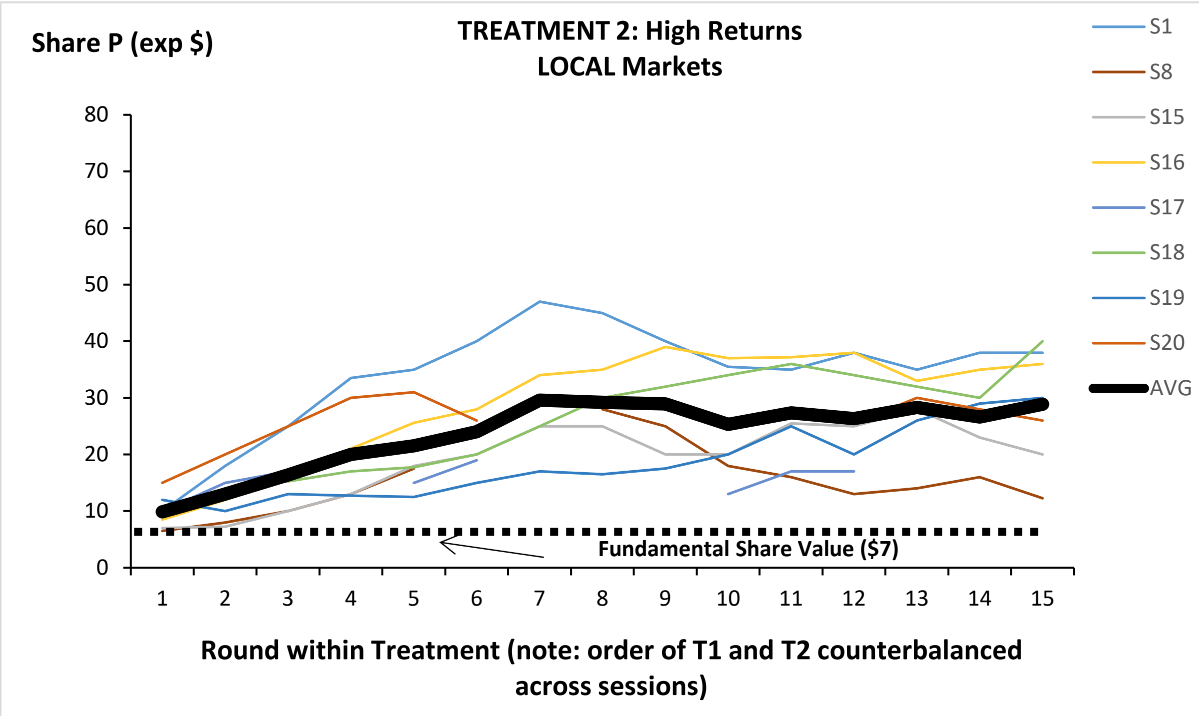
Panel B: Global Markets



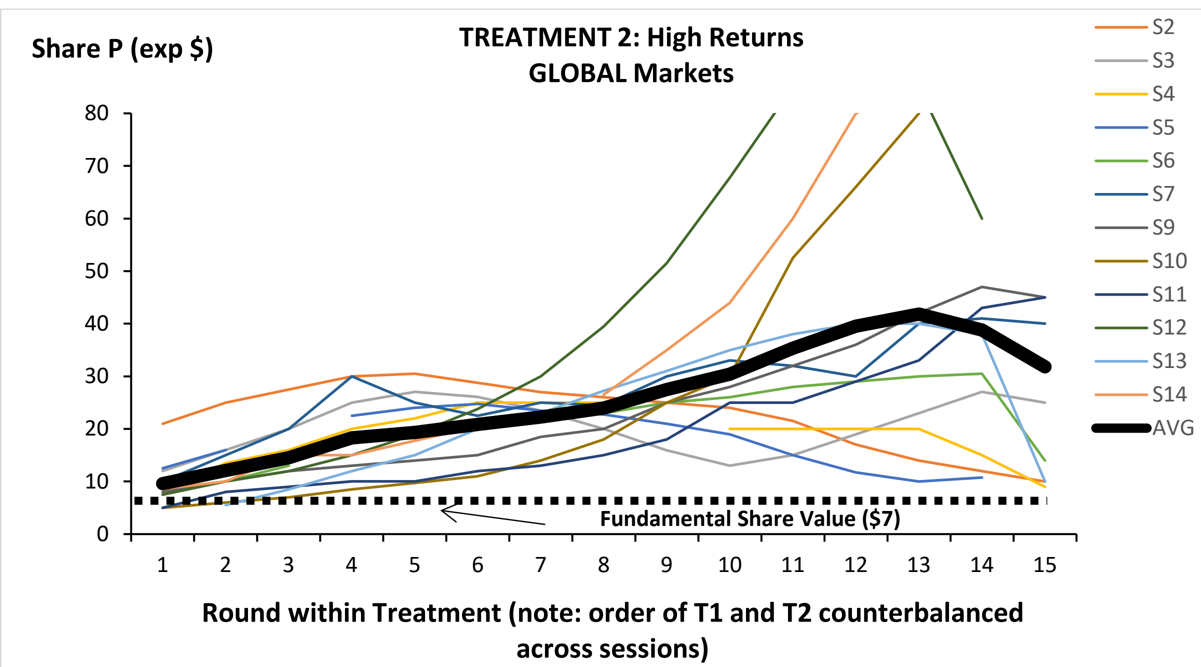
Notes: A gap in the market price graph typically indicates there were no shares traded in that period of that session. However, the gaps at price levels above $80 for some sessions in the GLOBAL Market data panels (both in Figures 3 and 4) are purely an artefact of our scaling the share price axis to a maximum of $80 for consistency and legibility.

FIGURE 4: Local versus Global markets: Prices across rounds in High Returns Treatment

Panel A: Local Markets



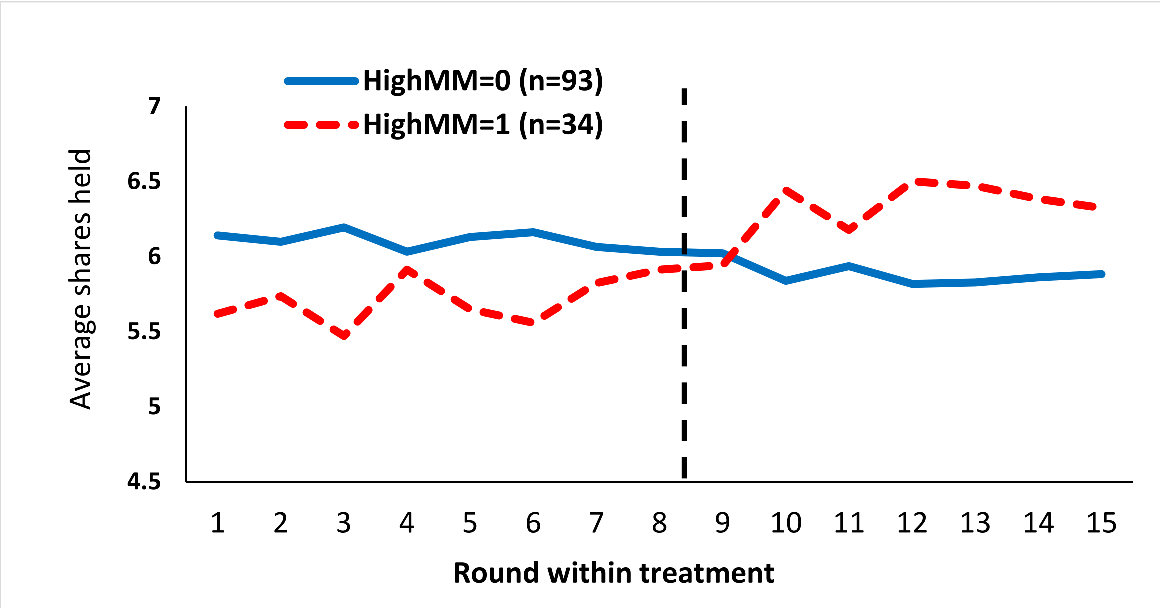
Panel B: Global Markets



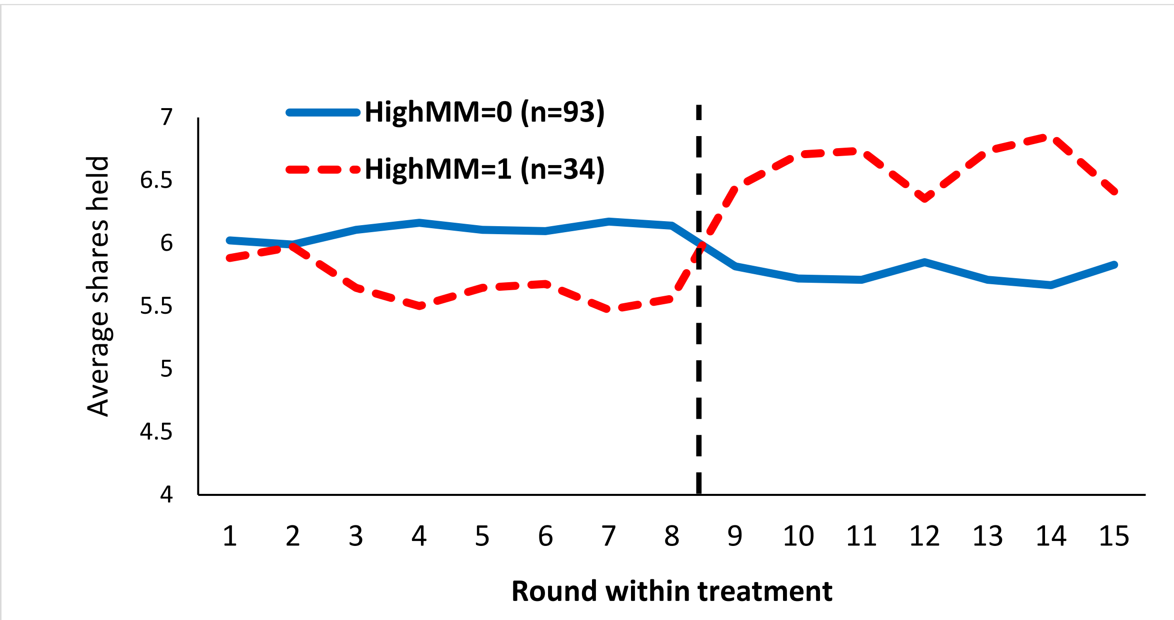
Note: Inadvertently, the High Returns treatment in Session 1 (Local Market) ran for 20 rounds instead of 15. While we include the market prices for rounds 1-15 of that session with other Local Market sessions, we do not include these for further data analysis. Because the High Returns treatment followed Low Returns in that session, the Low Returns treatment data for that session are unaffected and therefore have been retained.

FIGURE 5: Portfolio Share Holdings by Treatment

Panel A: Low Returns



Panel B: High Returns



Note: Data analyzed for differences in shareholding patterns are from Global Market sessions only; Session 1 omitted due to 20 rounds instead of 15, I High Returns treatment.

TABLE 1: Experiment Locations & Times

GLOBAL MARKETS (NZ AND USA) (Experiments administered at time of year when there was a 16-hour time difference between locations)		
USA local time	**New Zealand local time**	**# Sessions**
Noon	4:00am	2
4:00pm	8:00am	2
8:00pm	Noon	2
Midnight	4:00pm	2
4:00am	8:00pm	2
8:00am	Midnight	2
LOCAL MARKETS (NZ OR USA) (All subjects in single location)		
Location	**Local Time**	**# Sessions**
NZ	8:00pm	2
USA	Noon	2
USA	8:00pm	2
USA	4:00am	2

Note: Fixed payments for participation was $10 for sessions at local times of noon or 4:00pm; $20 for sessions at local times of 8:00am, 8:00pm, or midnight; $30 for sessions at local times of 4:00am. Additional earnings were based on outcomes in the asset market.

TABLE 2: Asset Bubble Measures and Local versus Global Sessions difference test

Treatment 1 (Low Returns)						**Treatment 2 (High Returns)**				
Local Markets	**Maximum Price**	**Duration**	**NAV**	**Turnover**		**Local Markets**	**Maximum Price**	**Duration**	**NAV**	**Turnover**
1	33	5	123.9	1.83		**1***	47	6	297.6	1.72
8	24.54	2	58.2	0.7		**8**	28	5	71.49	1.13
15	25	4	139.3	0.95		**15**	28	6	157.5	1.38
16	23.5	12	86.6	1.6		**16**	39	8	264.2	1.65
17	22	4	32.4	0.95		**17**	18.98	2	34.53	0.86
18	25.5	8	77.33	0.83		**18**	40	10	150.4	1.29
19	20	6	83.33	0.65		**19**	30	3	114.2	1.2
20	25	4	117.8	0.55		**20**	31	4	177.8	0.95
AVERAGE	***24.82***	***5.63***	***89.9***	***1.01***			***24.8***	***5.5***	***158***	***1.27***
Global Markets	**Maximum Price**	**Duration**	**NAV**	**Turnover**		**Global Markets**	**Maximum Price**	**Duration**	**NAV**	**Turnover**
2	32	9	175.5	1.03		**2**	30.5	5	171.8	1.14
3	26.12	10	98.51	1.64		**3**	27.05	4	148.6	1.24
4	20	5	53.04	1.5		**4**	25	5	96.3	0.85
5	23	8	104.8	1.42		**5**	24.75	4	114	1.39
6	18	9	57.93	1.11		**6**	30.5	12	146.3	0.79
7	45	7	119.1	1.24		**7**	41	3	187.8	1.7
9	37	7	175.3	0.86		**9**	47	13	191	1.52
10	53.5	5	164.5	0.7		**10**	80	12	182.4	1.58
11	25	6	87.5	0.75		**11**	45	12	132.7	1.42
12	58	6	172	1.15		**12**	97	11	404	1.19
13	22	5	69.23	0.77		**13**	40	10	165.5	1.08
14	95	7	312.3	0.7		**14**	112.3	12	356.3	1.03
AVERAGE	***37.89***	***7***	***132.48***	***1.07***			***37.89***	***8.58***	***191.39***	***1.24***
Mann-Whitney test of Global vs. Local Markets						**Mann-Whitney test of Global vs. Local Markets**				
Z	1.16	**1.713****	1.312*	0.733		Z	1.481*	**1.705****	1.099	0.254
1-sided P-value	0.12	**0.04**	0.09	0.23		1-sided P-value	0.07	**0.04**	0.14	0.4

Notes: (1) High returns treatment in Session 1 had 20 rounds instead of 15; the last five rounds have been excluded from these calculations; (2) ** and * denote significance at 5% and 10% respectively.

TABLE 3: Average share holdings in global markets (pooled across sessions for subjects of a given mismatch level)

	Low Returns Treatment			**High Returns Treatment**	
Round	**Alert (HighMM=0) (n=93)**	**Tired (HighMM=1) (n=34)**		**Alert (HighMM=0) (n=93)**	**Tired (HighMM=1) (n=34)**
1	6.14	5.62		6.02	5.88
2	6.10	5.74		5.99	5.97
3	6.19	5.47		6.11	5.65
4	6.03	5.91		6.16	5.50
5	6.13	5.65		6.11	5.65
6	6.16	5.56		6.10	5.68
7	6.06	5.82		6.17	5.47
8	6.03	5.91		6.14	5.56
9	6.02	5.94		5.82	6.44
10	5.84	6.44		5.72	6.71
11	5.94	6.18		5.71	6.74
12	5.82	6.50		5.85	6.35
13	5.83	6.47		5.71	6.74
14	5.86	6.38		5.67	6.85
15	5.88	6.32		5.83	6.41

T-test (unequal variance) of HighMM=0 versus HighMM=1

	Rounds 1-8	**Rounds 9-15**		**Rounds 1-8**	**Rounds 9-15**
T-Stat	6.44***	-5.44*		6.48***	-10.68

Note: ***, ** and * denote significance at 1%, 5% and 10% respectively.

Table 4: Patterns of share-holding in global markets; random effects regressions with errors clustered on sessions

Dependent variable: Shares Held

	Low Returns		**High Returns**	
HighMM	-0.397* (0.255)	-0.367* (0.253)	-0.42 (0.348)	-0.381 (0.344)
LateRound	-0.223 (0.193)	-0.223 (0.192)	-0.342 (0.264)	-0.342 (0.261)
HighMM*LateRd	0.833** (0.373)	0.831** (0.37)	1.278** (0.51)	1.278** (0.504)
Female	---	0.935*** (0.171)	---	1.502*** (0.233)
MathGood	---	0.427** (0.169)	---	-0.18 (0.23)
Epworth	---	-0.050** (0.022)	---	0.028 (0.03)
PerSD	---	-0.031 (0.065)	---	0.065 (0.088)
Experience	---	-0.006 (0.165)	---	-0.117 (0.223)
Constant	6.106*** (0.132)	5.786*** (0.279)	6.099*** (0.18)	5.055*** (0.369)
Observations	1905	1905	1905	1905
Wald χ^2	4.98	41.11	6.72	55.19
Prob > χ^2	0.17	0.000	0.08	0.00
Wald Test for Equality of coefficients				
HighMM+ HighMM*LateRd=0	$\chi^2 = 2.56$ $P > \chi^2 = 0.11$	*$\chi^2 = 2.93$ $P > \chi^2 = 0.09$*	**$\chi^2 = 5.19$ $P > \chi^2 = 0.02$**	**$\chi^2 = 5.93$ $P > \chi^2 = 0.02$**
LateRD+ HighMM*LateRd=0	**$\chi^2 = 4.44$ $P > \chi^2 = 0.04$**	**$\chi^2 = 4.5$ $P > \chi^2 = 0.03$**	**$\chi^2 = 5.61$ $P > \chi^2 = 0.02$**	**$\chi^2 = 5.73$ $P > \chi^2 = 0.02$**

Table 5: Price bias in global markets; random effects regressions with errors clustered on sessions

Dependent variable: Average individual bias = $QBid_t$*($BidPrice_t$ - $Price_{t-1}$) + $QAsk_t$*($AskPrice_t$ - $Price_t$)

	Low Returns		**High Returns**	
HighMM	-0.422 (8.959)	2.705 (9.11)	-11.72 (29.465)	-6.441 (29.398)
LateRound	-21.962*** (6.394)	-22.418*** (6.377)	-48.535** (22.613)	-45.574 (22.571)
HighMM*LateRd	4.284 (12.397)	5.616 (12.359)	139.753*** (44.035)	132.864*** (43.932)
Female	---	17.638*** (5.934)	---	54.923*** (20.213)
MathGood	---	3.677 (5.856)	---	-20.581 (19.924)
Epworth	---	0.854 (0.765)	---	0.818 (2.61)
PerSD	---	-1.466 (2.306)	---	-9.309 (7.506)
Experience	---	8.56 (15.387)	---	26.422 (19.647)
Constant	7.773 (6.383)	-14.51 (13.866)	-2.141 (15.527)	-33.786 (31.601)
Observations	1368	1368	1361	1361
Wald χ^2	14.61	25.58	15.91	31.57
Prob > χ^2	0.0022	0.0012	0.0012	0.001
Wald Test for Equality of coefficients				
HighMM+ HighMM*LateRd=0	$\chi^2 = 0.17$ $P > \chi^2 = 0.68$	$\chi^2 = 0.76$ $P > \chi^2 = 0.38$	**$\chi^2 = 15.31$** **$P > \chi^2 = 0.00$**	**$\chi^2 = 14.99$** **$P > \chi^2 = 0.00$**
LateRd+ HighMM*LateRd=0	$\chi^2 = 2.50$ $P > \chi^2 = 0.11$	*$\chi^2 = 2.86$* *$P > \chi^2 = 0.09$*	**$\chi^2 = 10.21$** **$P > \chi^2 = 0.00$**	**$\chi^2 = 9.20$** **$P > \chi^2 = 0.00$**

Table 6: Earnings in global markets; random effects regressions with errors clustered on sessions

Dependent variable: log earnings

	Low Returns		**High Returns**	
HighMM	-0.042 (0.095)	-0.048 (0.095)	-0.014 (0.108)	-0.019 (0.109)
Female	---	-0.188** (0.088)	---	-0.138 (0.1)
MathGood	---	0.051 (0.087)	---	0.059 (0.099)
Epworth	---	-0.001 (0.011)	---	-0.002 (0.013)
PerSD	---	-0.006 (0.033)	---	-0.016 (0.038)
Experience	---	0.009 (0.085)	---	-0.006 (0.097)
Constant	5.836*** (0.049)	5.932*** (0.136)	7.144*** (0.056)	7.231*** (0.15)
Observations	127	127	127	127
Wald χ^2	0.19	5.00	0.02	2.91
Prob > χ^2	0.66	0.424	0.90	0.82

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