

The Neurobiology of Play

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ABSTRACT

A large volume of neurobiological research has been conducted in recent years, almost all of which has been considered solely from the perspective of biology. However, most of the insights gained through this research are also valuable for the game research field. This paper discusses the implications of existing research in neurobiology to the play of games (including, but not restricted to digital games), and connects neurobiological perspectives with models of play aiming to construct superior player satisfaction models built upon biological foundations. Connections are presented between already recognized patterns of play and recent research on the brain (in particular, the limbic system). By providing a framework for understanding how the brain responds to recurrent patterns inherent to play, we aim to provide a platform for future experimental player-game interaction research (for which possible directions are briefly explored), and a propaedeutic to biologically-grounded player satisfaction models.

Categories and Subject Descriptors

K.8.0 [General]: Games – *Personal Computing*; J.4 [Computer Applications]: Sociology, Psychology – *Social and Behavioral Sciences*; J.3 [Life and Medical Sciences].

General Terms

Design, Human Factors, Theory.

Keywords

Play patterns, brain research, neurology, brain, player satisfaction modeling.

1. INTRODUCTION

In the last decade several models of player satisfaction [9] or emotion [38] have been discussed in light of helping game designers to create better and more enjoyable games. While most of these models are based on observation of players and years of intricate research, none of them are directly linked to a neurobiological understanding of players.

In this paper, we discuss relevant findings from neurobiological research and how these findings can be tied to designing digital and other games. It is important to appreciate that the back-

ground of the authors is not in neurobiology, and therefore this paper should be understood as a cross-disciplinary literature review with the intent of identifying the foundations of future research.

The main observations discussed here relate to various key brain structures in mammalian nervous systems:

- Nucleus accumbens and the dopaminergic reward system in general
- Orbito-frontal cortex (OFC), and in particular its close connection to the dopaminergic reward system
- Hippocampus and sensory cortices
- The “fight-or-flight” response, consisting principally of the amygdala and the neurotransmitters epinephrine and norepinephrine
- Testosterone
- Hypothalamus and the neurotransmitter oxytocin
- Mirror neurons located in the pre-motor cortex and the inferior parietal cortex.

This list may not be complete, and represents a first attempt at identifying the critical parts of the mammalian nervous system involved in play. While most of the research upon which this paper draws is in the context of *human* biology, the observations made could in principle extend to other animals.

Experimental work on exploring this subject has already begun, with a first step being an analysis of online survey data collected from game players (consisting of more than 25,000 data points; the results will be presented in a future paper). This data is based on a questionnaire constructed to identify tangible distinctions in player preference. However, it should be noted that – since self-assessment of play is a natural part of this process – both the provisional results of this study mentioned in this paper, and the future statistical analysis, should primarily be considered groundwork for future research.

An ultimate goal of this research is to conduct specific neurobiological research studies that relate play to events in the human nervous system. Some possible directions for this currently pending work are discussed at the end of this paper.

2. RELATED FUNDAMENTAL WORK

John von Neumann [51] was one of the first researchers to discuss a scientific theory of games by asking what the optimal strategy would be to achieve a desirable result for a player. An optimal strategy for each player according to his theory is to evaluate each game situation and choose the best move that is left. Thus, a player will try to maximize his minimal payoff while minimizing the maximal payoff of the other players. One of the

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factors not taken into account by this early game theory is the fuzzy human component of play. A key to understanding the design of digital games is to understand how games affect human emotion and cognition. Hence, we argue here that we need to take into account neurobiological findings to understand game design and players, and that we need to examine play as an emotional and cognitive activity.

In his fundamental work, Roger Caillois [17] defined four different elemental forms of playful behavior, which we refer to in this context as patterns of play based on the discussion by Bateman [8]: *agon* (i.e., conflict or competition), *alea* (i.e., chance), *mimicry* (i.e., imitation or role-playing), and *ilinx* (i.e., vertigo or sudden shock). Caillois also classified games along an activity dimension with two extremes, ranging from structured *ludus* (i.e., a rule-based playing activity) to unstructured *paidia* (i.e., spontaneous playful activity). We will go on to discuss how these patterns can be linked to brain mechanisms and the nervous system for explaining why these patterns of play are noticeable.

The question of what constitutes play is of critical importance to any attempt to study this aspect of behavior, and in this regard there is considerable ambiguity, as surveyed comprehensively by Sutton-Smith [64]. The *play* definition provided by Malaby [42] fits the purposes of our paper, namely that play is a dispositional attitude characterized by a readiness to improvise in the face of contingency. This in turn leads to Malaby’s definition of *game* as “a semibounded and socially legitimate domain of contrived contingency that generates interpretable outcomes” [41]. On this reading, *play* is a state of mind that individuals enter into, and *games* are socially grounded practices that contrive to allow participants to enter into a state of play.

On the anthropological perspective advanced by Malaby (which is thoroughly compatible with Caillois’ despite Malaby’s skepticism in this regard), a neurobiology of play must account for any playful situation relating to the circumstances of any arbitrary game (i.e., *gameplay*) and also to any situation of play, *independent* of a formal game system (i.e., *toyplay* [9] or *paidia* [17]). Almost all necessary neurobiological mechanisms for such an account are already available, and will be discussed later in this paper. We acknowledge that alternative perspectives on play could be equally compatible with the observations presented in this paper. Therefore, our decision to ground the definitions of *play* and *game* with Malaby makes no claim of objective superiority, but were chosen to fit the taxonomical purposes of this paper.

For a better understanding of our theoretical foundation, making the connection between the patterns discussed here (in the context of neurobiology of play) and the first player model deployed in this field, Richard Bartle’s typology [7], is necessary (four types: Killers, Achievers, Socializers, Explorers, see Figure 1). His model was constructed on an ad-hoc basis, based solely upon informal observations of players of early massively multiplayer games collectively referred to as MUDs (multi-user dungeons or domains). However, these observations retain a certain anthropological validity, whatever the limitations of the approach.

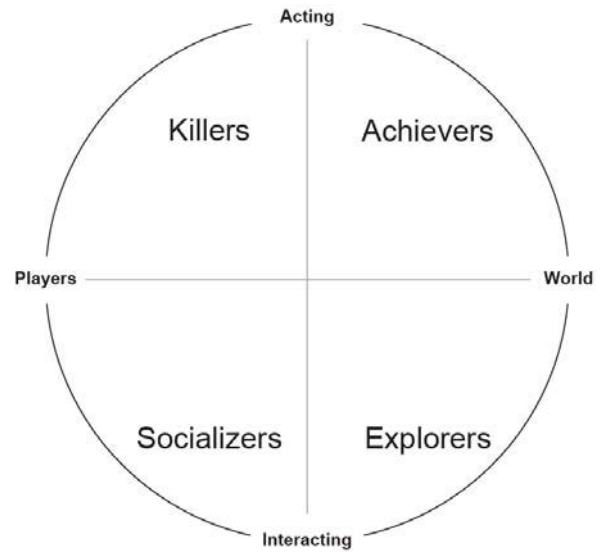


Figure 1. Bartle’s four player types (i.e., Killers, Achievers, Socializers, and Explorers) created from observing players of MUDs [7].

While the brain regions discussed here do not correspond directly to Bartle’s system, there are nonetheless important debts owed to this foundational model. In particular, Bartle’s Achievers and Socializers appear to correspond to a preference for activation of specific brain regions, while Bartle’s Explorers may conflate two distinct neurobiological systems. However, Bartle’s Killer type does not appear to implicitly relate to any given brain region, although may relate to testosterone.

Similar observations could be made in respect of other generalized as well as specific player satisfaction models, such as those of Bateman [9] or Yee [73], but the widespread discussion of Bartle’s system [7] in the existing literature warrants explicit discussion in the context of identifying related work, while the specifics concerning the relationship with other systems lies beyond the scope of this paper.

Before proceeding to discuss specific observations, we will quickly introduce a few important brain areas.

2.1 Important Brain Areas

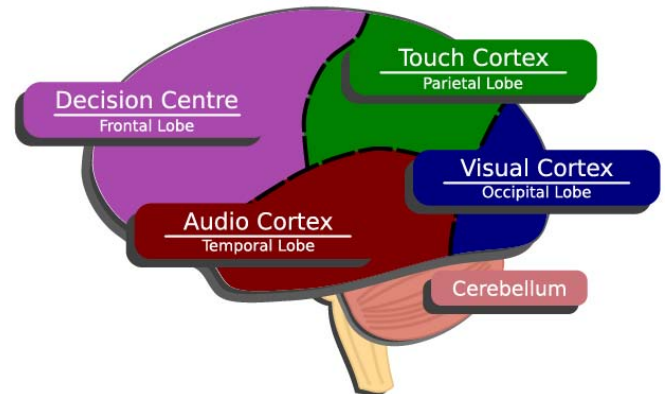


Figure 2. Major brain regions and their corresponding functionality (as depicted in [8])

The cortex of the human brain is conventionally divided into 4 key areas known as lobes (see Figure 2):

1. Activity in the frontal lobe is commonly associated with cognitive functioning and decision making, in particular the orbitofrontal cortex (OFC) [70]. However, while the OFC is a critical structure in the neural systems underlying decision making, it is not responsible for this alone, and forms a part of a large-scale system that includes cortical components, such as the amygdala, insular cortices, and the peripheral nervous system [11]. Due to its critical function, we will refer to the frontal lobe as the decision center of the brain for the rest of this paper, while acknowledging that some simplification of functionality is entailed in this representation.
2. Behind the frontal lobe and above the occipital lobe, the parietal lobe is located mid-back of the brain. It includes the somatosensory cortex and part of the visual system (dorsal stream), which associates this area with spatial and navigational sensing as well as an emotional wiring to one's own body being touched and the sight of intentional touch [23]. This area is referred to as the touch cortex for the remainder of the paper.
3. The temporal lobe is located sideways (left and right hemispheres of the brain) and below the frontal lobe beneath the lateral sulcus. It is responsible for the auditory processing of the brain and includes the primary auditory cortex, which responds to basic hearing, volume, pitch, and processing of speech sounds [13]. This area of the brain will be referred to as the audio cortex.
4. The occipital lobe is the smallest lobe, located at the back of the human skull, near midline and beneath the parietal lobe. It contains the primary visual cortex, which processes visual sensory information [31], which is why we will call this area the visual cortex.

Another brain area of interest not included above is the cerebellum (or little brain) is situated underneath the occipital lobe and has a major function in coordinating motor control (and motor learning). A study conducted on brain activation during playing the game *Tetris* [55] found that the cerebellum was highly activated while learning necessary control skills for the game, and showed attenuated activation once the skills were acquired [66].

2.2 Centers in the Limbic System

In the inner body of the cerebral cortex located atop the spinal cord and brainstem, we possess a set of brain structures commonly referred to as the limbic system. It is one of the oldest brain structures having evolved even before reptiles were the most advanced life forms on the planet [16]. The limbic system triggers chemicals (i.e., neurotransmitters) that ascertain functionality of our emotions, behavior, olfaction, and even long-term memory. Most important for our purposes is the correlation of emotional experiences with the neurological activation of the limbic system. The major functions of the limbic system are shown together with their inner cortical location in Figure 3, such as:

- The nucleus accumbens has been shown to correlate with the formation of habits and behavior [29], especially involved

with rewards [19], pleasures [12], and addiction [68]. We will call it the pleasure center.

- The amygdala plays a key role in emotion-related learning, memory, attention, perception, and prediction [10]. While it is particularly often associated with fear, it has also been shown to influence learning and decision-making for aversive (i.e., negative) as well as appetitive (i.e., positive) outcomes [56]. For our purposes in classifying play, it suffices to call it the fear center.
- The hippocampus is responsible for our associative memory and modulates the information transfer to the neocortex to store long-term episodic memories [65]. We will refer to it as the association area.
- The hypothalamus regulates primary bodily functions such as appetite, but it has also been shown to affect anger and trust. For example, hypothalamic activation was linked to physical aggression [67]. While it might at this point be a bit misleading, we will refer to it as the social center.

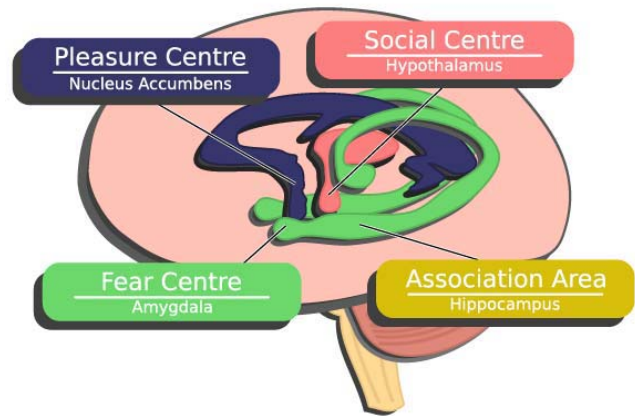


Figure 3. Key Elements of the Limbic System (from [8])

Maguire et al. discovered that London taxi drivers, who have acquired considerable spatial knowledge of the city's streets, displayed larger posterior hippocampi than other people [40]. Based on their research, we can venture to suppose that the parts of the brain which are used constantly may grow in size and possibly in processing speed. In addition, we must acknowledge the individual brain differences that may stem from genetic variation, learning, and skill acquisition. Ultimately, games may alter the function, size, and shape of a subject's brain and this in turn suggests possible research avenues of critical importance to the field of player satisfaction modeling, which ordinarily lacks mechanisms that are empirically grounded in anything other than statistical correlation.

3. REWARD SYSTEM

At the core of any neurobiological description of games – and by extension of play – lies the dopaminergic reward system. This subject is well treated in neurological and biological literature, but considerable expansions to our knowledge of its mechanisms have recently become known, with significant implications for a neurobiological description of play.

3.1 Dopamine

The pleasure center of the brain (the nucleus accumbens) is well-established as the critical brain region associated with the neurotransmitter dopamine, which in turn is implicated in habit formation, reward-seeking behaviors and addiction [53] [27][3]. Recent research by Koeppe et al. [35] has confirmed the suppositions of Koster [37] and other seasoned game designers that the dopaminergic reward structure in the limbic system plays a key role in the reward orientation of digital and other games. Furthermore, the work of Skinner et al. [62] explicates the role of reward structures [63] in mediating the activation of the pleasure center, which has been explicitly used by some game designers as means of motivating players [32]. The reward-seeking behavior associated with dopamine also appears to correlate with Bartle's [7] Achiever player type. However, this kind of structured approach to rewards is only one of many ways in which the pleasure center can be tied to play.

3.2 Decisions

Game designer Sid Meier asserts the role of decisions to gameplay in his quote that "a game is a series of interesting choices" (quoted on p.38 in [59]). While the universal applicability of such a claim is dubious (i.e., it is not clear that for example a rhythm-action game or a memory game such as *Simon* [5] offer any meaningful choices at all, let alone choices that could be deemed interesting), but this assertion points to the key role of another part of the brain: the decision center (i.e., the OFC).

The decision center is closely tied to the limbic system and the pleasure center in particular [60] and by extension to addictive behavior [68]. The upshot of this research is that the mammal brain is constructed in order to ensure that making good decisions is especially rewarding. Thus, solving puzzles and devising strategies is a means of producing the emotional reward of *fiero* (i.e., triumph over adversity) described by Lazzaro [38] as Hard Fun¹. It is plausible to assume at this stage that the emotion of *fiero* as originally described by Ekman [24] corresponds to a large release of dopamine from the pleasure center (a hypothesis recently advanced by Bateman [8]).

However, the influence of the decision center on play extends beyond its direct function in strategic play. Clark et al. have demonstrated that the pleasure center is also activated when players *nearly* win, both in games of skill and games of chance [19]. The release of dopamine peaks with *near misses* which are closer to the goal state. Unusually, despite the release of dopamine, players find the *near miss* experience subjectively unpleasant. This negative effect could be explained in terms of frustration; the effect of the pleasure center activation in this instance is reinforcing the current behavior (i.e. encouraging the player to persevere and attain success; see below regarding testosterone).

3.3 Uncertainty

Another way of activating the reward system is via uncertainty, which can be found most prominently in gambling games. However, many forms of play contain elements of what Caillois [17]

labels *alea*, games of chance, as can be seen with the near-universal deployment of card or dice based game mechanics in boardgames.

Uncertainty in play can generate *fiero* if the stakes are sufficient to make players emotionally invested in positive outcome (i.e., gambling for money), or if the chance of success is sufficiently low. This route to *fiero* is not entailed in Lazzaro's Hard Fun [38], since her system was based on observation of digital game players, and this kind of play has traditionally minimized the role of chance. However, *fiero* has been readily observed among players of tabletop role-playing games, boardgames, and gamblers [8].

Shizgal et al. report the pleasure center was activated in anticipation of uncertain rewards, which they suggest promotes the learning of better predictors of reward [61]. This effect is an explicit part of the enjoyment of gambling and chance-mediated games, but additionally this mechanism is implicated in play in general, since following Malaby's [42] definition all play entails a response to contingency.

The implications of these results for a neurobiology of play lie in the definition of a role in coordinating behavior toward a goal for the decision center: A player whose decision center establishes a possible (but uncertain) reward experiences a release of dopamine, potentially motivating them to pursue the reward. In games of chance, this mechanism is sufficient to explain the player behavior in general terms; in the case of games of skill, as the player gets closer to attaining their goal, behavior is reinforced by the near miss effect [19].

Collectively, Clark et al. and Shizgal et al. provide a neurobiological explanation of short-term compulsion, supplementing the long-term addiction reasoning implied by Skinner's reward schedules. This mechanism is beyond the role of reward schedules in mediating play. It shows how the brain works to adjust subjects toward success.

3.4 Interest

An additional significant activation of the pleasure centre has been tied to interest and curiosity by Biederman et al. [12], who conducted *fMRI*² scans of people who were viewing various different scenes. They discovered a neural pathway involving the neurotransmitter *endomorphin*, which was triggered by the association areas (hippocampus) when study participants were presented with a richly interpreted image. They later demonstrated that enjoyment generated by this interest mechanism triggered the pleasure center [74].

In terms of emotions of play, the interest mechanism [12] [74] dovetails with Easy Fun [38], the play of curiosity, for which the key emotion is wonder. This has been observed to trigger a full-body response of significant intensity. Bateman has also recently hypothesized that this could correspond to a large release of dopamine from the pleasure center [8]. By linking curiosity to the dopaminergic reward system, a wide range of playful behaviors can be represented.

Bartle's Explorer [7] type appears to be a confluence of this interest mechanism and the puzzle-solving role of the decision

¹ Although – as noted below – this is only one form of Lazzaro's Hard Fun, which neurobiologically may conflate two distinct mechanisms.

² functional Magnetic Resonance Imaging

center discussed previously – a convergence that may reflect an interest in scientific fields in general, since these are also mediated by the confluence of curiosity and problem solving.

4. STRESS RESPONSE

The stress response – commonly termed the *fight-or-flight* response – has been well established for nearly a decade as a key part of animal biology [18]. It is as intimately tied up with play as the reward system, although a markedly smaller volume of the literature in respect of games deals with this facet.

In both *fight* and *flight*, the hormone and neurotransmitter *epinephrine* (i.e., adrenalin) is fundamental, and in the case of *fight* the chemically related neurotransmitter *norepinephrine* is also involved. Both *catecholamines* are principally produced in the adrenal glands. The emotional states associated with these neurotransmitters are anger (fight) and fear (flight) [4]. However, release of epinephrine is also associated with a state of excitement: it is activation of the fear center (i.e., amygdala) in the limbic system that transforms an experience of excitement into one of anxiety [34], while the underlying neurochemistry of these two otherwise distinct emotional states appears to be essentially the same.

In all cases, the *corticosteroid* hormone *cortisol* is also released, which has synergetic effects with the aforementioned neurotransmitters and is also synthesized in the adrenal glands. These effects include short term memory of emotional events relating to confluence of *epinephrine* and *cortisol* [47] and increased blood pressure as a result of *cortisol* increasing the sensitivity of the blood vessels to both *epinephrine* and *norepinephrine* [1]. Because of the parallel action with *cortisol*, the latter hormone is frequently used by researchers as an indicator for stress response.

4.1 Excitement

Excitement is associated with epinephrine, an almost trivial observation given the widespread use of the term *adrenalin* (i.e., epinephrine) in the context of extreme sports and danger. Lazzaro considers excitement as part of what she calls Serious Fun, and links it with relief, which is known to be intrinsically rewarding [38]. In this regard, the neurobiology is intimately involved with fear – the experience of relief being essentially the removal of any given cause for anxiety. This also connects with Caillois’ pattern *ilinx*, which he relates to vertigo, itself a form of fear [17].

The closest ties between excitement and play approach the issue in an inverse fashion beginning with Csikszentmihályi’s concept of *Flow* [21][20]. Optimal experience (i.e., Flow) is claimed to lie at a point of balance between boredom and anxiety. This could be a state between insufficient arousal (i.e., low levels of epinephrine) and activation of the amygdala in fear (i.e., moderate to high levels of epinephrine).

Bateman has hypothesized that epinephrine enhances the reward system [8]. This means excitement would enhance enjoyment of rewards. However, this is currently unsupported by the literature. Nevertheless, a relationship between dopamine and fear conditioning has been demonstrated lending support to this claim [28].

4.2 Frustration

The experience of anger in the context of play is usually registered at a conscious level as frustration, and Lazzaro has noted the role of anger in Hard Fun [38]. Previously, we observed that Hard Fun related to the *fiero* elicited from determining a complex strategy (implicating the decision center), but it is also noted that *fiero* is produced by difficult challenges, which typically frustrate the individual. While many individuals are capable of concluding they enjoy excitement, it is less clear to most players that frustration may be enjoyed.

Regardless, when a game presents significant challenges generating frustration, those players who persevere and ultimately overcome the problem experience *fiero* [38]. This situation is a parallel to the aforementioned case of *fiero* experienced by players who solve puzzles and devise strategies. Following Bateman’s hypothesis that *fiero* corresponds to a significant release of dopamine, at a neurobiological level Hard Fun may be divided into two distinct mechanisms: (1) that of the decision center, and (2) the frustration-enhanced *fiero* (corresponding to the *fight* stress response). This latter mechanism may also have connections with gender, as the following section explicates.

5. TESTOSTERONE

Research in the 1970s demonstrated a connection between the androgen testosterone and persistence [2], and recent literature reviews have explicitly made the claim that higher levels of testosterone can be correlated with tenacity [47]. This suggests the attainment of *fiero* from challenge may connect with testosterone, since only those players willing to persevere will overcome a difficult challenge and attain the emotional (likely dopaminergic) reward.

Recent studies reinforce this claim, and testosterone is emerging as a major neurobiological factor in competitive play, interpreted by most researchers in terms of dominance behaviors. This research has been principally focused upon male primates [33] and testosterone in females is less well understood [46]. Key findings demonstrate levels of testosterone not only affect the degree of competitiveness, but the outcome of competitive play affects levels of testosterone. For example, in sporting contests, male athletes show predictable changes in testosterone levels, with levels of the androgen rising prior to a match [15] while after a match the testosterone levels of winners are higher relative to the losers [25].

These effects are not restricted to physical contests, as the same patterns have been demonstrated in chess matches [45], contrived contests based around reaction time [30] and challenges of honor initiated by an insult [52]. The reported changes of testosterone appear to relate to how emotionally invested in the competition individuals might be, with testosterone spikes corresponding to the attainment of *fiero* (“elated mood of victory”) [15], and if the participants do not consider the win important there is no rise in testosterone [44].

Neither is testosterone a requirement for *fiero*. Puzzle-solving and strategic thinking can generate this emotion, as can games of chance including gambling. No relationship between testosterone levels and pathological gambling has been found in prior studies [14], reinforcing the claim that while testosterone may be involved in the *fiero* generated from face-to-face competition, this

is merely one of many neurobiological mechanisms lying behind play.

5.1 Gender Distinctions

Differences in the relationship between testosterone and competitiveness between the genders have been explored in the context of digital games [46]. Using a pong-variant, testosterone and cortisol levels of subjects participating in competitive play against an opponent of the same gender were examined in this study. The male subjects did not show the usual pattern of testosterone – while it did rise prior to the contest, there was little change afterwards (and little mood difference). The authors suggest that since most of their male subjects were regular digital game players the simplistic game used may have failed to generate any sense of meaningful competition.

Among the female subjects, positive mood was reported by victorious players but there was no post-match elevation of testosterone of winners relative to losers – neither was any pre-match elevation evident in testosterone. However, cortisol levels among females were consistently higher than males, which suggests that women were participating competitively (since they were experiencing greater stress levels). The authors conclude that testosterone works differently in competitive play between men than it does in competitive play between women.

Note, however, there is no indication that women in this experiment experienced *fiero* upon attaining victory. The elevated cortisol levels may simply show women were enjoying the game more than the men (i.e., they were more excited by the contest). There is no reason to assume female subjects were emotionally invested in the outcome of the contest (and thus the absence of testosterone changes would be expected). As it stands the result is inconclusive.

The research to date suggests both that testosterone is a key driver of competitive play among men, and also that competitive play among women entails neurobiologically distinct mechanisms from those of men, for which further research is needed.

5.2 Coalitional Play

Additional research has been conducted on the role of testosterone in coalitional play among men, that is, when people compete as teams against one another. (This is distinct from cooperative play, which may occur in a situation which is not expressly competitive).

A pioneering study of two-on-two domino games in a rural Caribbean village found distinctions between the testosterone levels when teams played against opposing teams from the same village when compared to playing against teams from another village [69]. Both testosterone and cortisol levels were higher when teams competed against opponents from a different village, although the study was unable to compare responses for victory and defeat since the same teams were victorious in each case.

Similar experiments have been conducted in digital game competitions using *Unreal Tournament 2004* [54]. Fourteen groups of three male players (who had not met each other before) were matched against each other after having practiced together for about six hours, with a cash reward being offered to the winners as incentive. Again, winning players experienced a testosterone spike when competing against the other teams, but when the

players within a team competed with each other the highest scoring player tended to produce less testosterone than their defeated teammates.

In conclusion, all these experiments suggests that men have elevated testosterone levels and are more competitive when facing opponents for whom they have no prior relationship. This may bear upon the behavior of Bartle's Killer type players.

6. SOCIAL FACTORS

The sections above detail those aspects of a neurobiology of play that have received the most attention among the research community. However, there are many topics of significant importance to the construction of a complete description of play at a biological level that have yet to be adequately studied. Most of these remaining issues concern social aspects of play.

6.1 Co-operation

While competition is frequently considered in the context of play, co-operation is more rarely taken into account outside of coalitional situations, such as those mentioned above. Nonetheless, co-operation is of vital importance in a great number of play activities, including participatory storytelling (such as in tabletop role-playing games), co-operative play in digital games (including Bartle's Socialisers [7]), and almost all intersections between music and play (including but not restricted to improvisational music and dance).

Oxytocin has been emerging in the literature as a key neurotransmitter associated with pro-social circumstances, and hence with co-operation. It was demonstrated that oxytocin can increase trust [36] although the circumstances appear to be critical to the relevant pro-social effects: in the absence social information, oxytocin appears to promote risk-averse behavior (i.e., it does not generate trust by itself, but merely encourages trust under appropriate social circumstances) [22].

Because the hypothalamus is a key producer of oxytocin, and also has a role in moderating anger, this part of the limbic system can be crudely considered the social centre. There may be interesting interactions between the reward system and the social centre yet to be studied, since research on prairie voles has shown that dopamine and oxytocin interactions are associated with pair bonding [39]. There may be some truth in the old adage that “the family that plays together stays together.”

6.2 Mimesis

Only one of Caillois' patterns has not been covered in previous sections: *mimicry*. This essential play element lies behind all kinds of imaginative activities, from the make-believe of children to the perception of digital game worlds. Yet neurobiologically, there are still only scant leads as to how this play aspect should be understood.

One promising element of the puzzle might be found in mirror neuron research [58], although this field is still in its infancy. In terms of a neural basis for imagination, evidence that imagined images utilize the visual cortex in a manner similar to perceived images has already been reported [6]. This suggests that all the sensory cortices can be deployed for imagination as well as perception. Why some people find imagination and imaginative play easier than others remains unexplained, although it seems proba-

ble that abstract language use (which expresses in about a quarter of the population) will correlate with an active imagination in adults at the very least.

Finally, it is worth noting that the philosopher Kendall Walton has developed a theory of representational art that explains our ability to appreciate art, music, theatre, film and so forth in terms of a parallel with the way children use dolls and toys as props in a game of make-believe [71]. The well-established philosophical puzzle of how we are able to enjoy stories and pictures, which was commented upon by Wittgenstein [72] is potentially resolved by Walton's make-believe theory of representation. If a neurobiological description of imagination and mimesis can be provided it might allow a complete neurobiology of play to explain not only play and games, but art, music and stories as well.

7. FUTURE RESEARCH

Numerous avenues of research emerge from our discussion, but some are easier to pursue than others. Testosterone and cortisol can be easily assayed with a saliva test, which in part explains why so much research already exists in these areas. Digital games are already being used in research of this nature, and there is a great deal of exploratory work that could still be conducted. For example, since a minority of female players are interested in highly competitive and visceral play, such as that found in first person shooter (FPS) games, a study of testosterone levels among FPS players of both genders could yield interesting data.

At a greater level of complexity, highly informative studies could be conducted using functional Magnetic Resonance Imaging (fMRI) [43], electromyographic (EMG) [57,49] and electroencephalographic (EEG) [48, 50] research methods, which are currently becoming more popular in game research. Equivalent studies on game players could potentially demonstrate that certain play style preferences might correlate with enlargement of specific brain features (e.g., reward-seeking behavior and the nucleus accumbens, puzzle-solving and the OFC). Indeed, some research of this nature has already been conducted correlating size of the striatum (which links the OFC to the pleasure center) with the acquisition of specific player skills [26]. Suitable studies should confirm neurobiological correlates to play style preferences, and this could help construct superior player satisfaction models in the future.

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