BRAIN SCIENCE PODCAST

With Ginger Campbell, MD

Episode #63

An Interview with Dr. David Bainbridge, Author of *Teenagers: A Natural History*, and *Beyond the Zonules of Zinn*

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INTRODUCTION

This is Episode 63 of the *Brain Science Podcast*, and I'm your host, Dr. Ginger Campbell. Today we are going to be exploring the mysteries of the teenage brain.

But first I want to remind you that you can find show notes and episode transcripts at our website at brainsciencepodcast.com. You can also send me email at docartemis@gmail.com. And I have a brand new phone number you can call: It's 206-984-0358. I will tell you more about that at the end of the show.

Today my guest is David Bainbridge, who teaches veterinary anatomy and reproductive biology at Cambridge University in the UK. He is also the author of four popular science books, including *Beyond the Zonules of Zinn: A Fantastic Journey Through Your Brain*, which I talked about back in Episode 32.

Today we are going to be talking about his newest book, *Teenagers: A Natural History*. After the interview I will be back with a few announcements, including the details about the new *Brain Science Podcast* application for the iPhone.

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INTERVIEW

Dr. Campbell: David, it's great to have you on the *Brain Science Podcast* today.

Dr. Bainbridge: It's great to be here.

Dr. Campbell: Could you start out by just telling us a little bit about yourself?

Dr. Bainbridge: I've had a fairly mixed career. I trained as a veterinary surgeon about 20 years ago, and since then I've worked in practice a little bit. And then I started to research my PhD doing reproductive biology in deer, and then moved across to reproductive biology—especially pregnancy—in humans. And I've now ended up being the veterinary anatomist at Cambridge University.

Also about 10 years ago I started writing popular science books. I've written four popular science books: One on pregnancy and reproduction, one on the X chromosome, one on the brain (which I think was featured on the *Brain Science Podcast* before), and now one on teenagers.

Dr. Campbell: Great. So, what percentage of your time do you spend on your writing?

Dr. Bainbridge: Not as much as I'd like, really. It's just something I do when I'm not doing the day jobs. I don't know; probably 10% or 15% of my time. Some of these books can take quite a lot of time to get written.

Dr. Campbell: Yes. And people don't realize that the kinds of books you write, it's hard to really make any money on, isn't it?

Dr. Bainbridge: Yes. It's a strange world, publishing. It's the opposite of fiction. It's not too bad getting a contract to get your book published, but then once it's actually published, making money out of it is very difficult.

Dr. Campbell: Let's talk a little bit about your new book. Your last book, *Beyond the Zonules of Zinn*, was about neuroanatomy, as you said. And I can see how, as a veterinary anatomist, an interest in comparative anatomy would lead you to an interest in the human brain. But I'm wondering what led you to write your latest book, *Teenagers: A Natural History*.

Dr. Bainbridge: Really my previous books led me up to writing it. I'd written a book about the brain, I'd written a book about sexuality, and I'd written a book about reproduction. And I started going into the idea of writing the *Teenagers* book because I thought, well this is the decade of human life when everything kind of collides. You're doing everything at the same time. You're developing in all sorts of ways—your brain, and all sorts of ways—but also being an adult at the same time.

But as I did more and more research on it I found it was actually much more interesting than that. It's not just a time when everything collides. In a way it's the most important time of your life. And I think really that's true of the brain, as well. There's just so much going on in there.

Dr. Campbell: There's a lot of disagreement about adolescence. Some people even argue that it's just a recent product of modern culture. But your book argues just the opposite. I think on Page 14 you say that adolescence is "the essential characteristic of the human race on which our success is built." Would you expand on that idea?

Dr. Bainbridge: It's really because at the beginning I tried to make a list of what was unusual about people. And, obviously, many of the things that are unusual about humans as a species are about the brain. Many of the other things have to do with reproduction. And lots of these things really seem to kick in around the teenage years. It's fairly obvious that people can do a lot more when they're 20 than when they're 10. Obviously they're pretty clever when they're 10, but they're even more clever by the time they're 20.

And to back that up there are really two lines of evidence. There's the fossil evidence, and then there's the modern brain scanning evidence. Now, the fossil evidence is that when you look back at human fossils you find that the time when we made our great leap to having the *Homo sapiens* brain—the 1200-1300 mm brain that we have now—coincided fairly exactly with the time when we first took more than 10 years to mature. So, really teenagers and the big brain appeared at the same time.

The modern half of the evidence is, of course, now in the last 10 to 15 years we've been able to brain scan teenagers as they grow up. And you can see this tremendous reconfiguration of this huge human brain in a way that you really don't see in other species. So, taken together, all these weird features of humans, and when they occur, and when they evolved, I came down to my central hypothesis, which is that without teenagers we wouldn't be human.

Dr. Campbell: So, that's going to surprise a lot of readers, I suspect.

Dr. Bainbridge: I think it is. But, of course, teenagers, because they're making us human, they're letting us do all these amazingly clever things we do—abstraction, goal-directed planning, incredibly complex use of language, selective language, incredible social feats that they carry out—because they're doing all that and they're having to learn all that (it's very stressful, very demanding, and probably makes them feel pretty grouchy quite a lot of the time), there's just so

much reconfiguration going on, I think it makes life quite difficult for them; and also, of course, difficult for anyone who has got to be around them.

Dr. Campbell: Because we're on the *Brain Science Podcast* I'm going to focus on the teenage brain. But I want to mention that David's book is actually a very comprehensive look at what it means to be a teenager. So, I recommend that you read it to get to the other aspects of the question.

But we're going to focus on the brain. Since our bodies undergo extreme changes during adolescence, I guess it makes sense that our brains change also. Can you give us an overview of what happens?

Dr. Bainbridge: In a way the brain changes are more surprising than the bodily changes, because the bodily changes are obvious; everybody knows about them. The brain changes we've only really become aware of since we've been able to do proper brain scans.

The most surprising gross change is that the brain actually shrinks. The brain is probably at its largest when you're about 12 or 13, and it shrinks after that time. So, that, of course, makes the 12- and 13-year-olds very happy, because they can say they've got bigger brains than their parents. But there's much more to it than just your brain shrinking. It's a much more positive change than that. There is a series of carefully orchestrated and choreographed changes which are going on.

The first of these is a process called synaptic pruning. This is where all the connections—the synapses that form in huge profusion in children—don't completely stop forming, but the rate of formation slows down dramatically, and they're trimmed back, or pruned, very savagely for a period of about eight years during the teenage years.

And the connections that are being cut away, it's a very selective, organized process. It's not just the connections that aren't used very much. It doesn't seem

to be that simple. And also waves of pruning sweep across the brain. They do one bit of the brain first, and then they march across to another part of the brain. So, that's a very ordered process, but it actually means that the gray matter gets thinner. And that's probably the main reason why the brain actually gets smaller. So, that's the first big change.

The second big change is that many of the pathways lying underneath the gray matter in the white matter were present in childhood, but they weren't myelinated: They didn't have their fatty electrical insulation around them. And there are many connections deep in the brain where that myelination—that insulation—forms during the teenage years.

One of the effects of this insulation is (strangely enough, for various electrochemical reasons) it actually makes the nerves conduct a lot faster. And so, we think many of these pathways, although they're there in children, they don't really do much. It's not until they're sort of up to speed and switching on that the brain really starts using them. And so, there are bits of the brain that just weren't used much in childhood, that are suddenly switched on. So, that's the second big change.

Finally, the third big change is that there are certain pathways, which have been there all along, which seem to start to behave differently. Many of these actually involve dopamine. Dopamine seems to be a neurotransmitter—a chemical—that comes up a lot when you're dealing with teenagers. And dopamine projections from deep in the brain up to the cortex on the surface seem to become more active. That's much harder to study than these anatomical changes. But it is thought to occur, as well.

So, there's a lot going on in there. There's lots of roadwork going on inside the brain. Some of the typical aspects of teenagers that you see may just be that the brain is not working that well because it's in a state of having roadwork done. It's

like a road: It's just not working very well because there's a roadblock and men digging up the road. So, that may be one of the reasons why teenagers behave the way they do.

Dr. Campbell: Taking the pieces that you've just listed, one at a time, you talked about the pruning. So, in essence at the beginning it's almost as if they have too many connections, rather than too few?

Dr. Bainbridge: It is. Synaptic pruning—this process of growing a profusion of connections and then trimming them back—you actually see this throughout the animal kingdom to some extent. So, I'm not claiming that the actual process in itself is unique to humans. But in humans you see this very dramatic division between the two phases—the proliferation phase in childhood and the trimming-back phase in teenage life.

Dr. Campbell: And then I guess when it comes to the myelination and the using parts that we haven't used before, people usually think of the prefrontal lobes as being a big one in this regard.

Dr. Bainbridge: Yes, that probably is the case. That's the myelination, and also probably the dopamine effect, as well. I'll qualify this in a second; but some people have claimed that one of the effects you see in teenagers is that the way they deal with emotion and fear and anger changes, and that instead of using regions deep within the brain—like the amygdala and the so-called limbic system—they start being able to temper their emotion and their anger by using their prefrontal cortex to control it. Of course, the prefrontal cortex does a lot more than that. So, that's the idea, that different bits of the brain are switching on at different times.

One thing I should say about all of this is that there's one caveat I should add, which I tried to do my best in the book to add, because I just never see it written

in other books about the teenage brain. We obviously have lots of information about the structural and even the functional changes that are going on in the teenage brain at a sort of low level. We also have lots of anecdotal data, and now psychological data, about how teenagers behave and think. But, of course, anybody who knows much about the brain will realize that the thing we don't have yet is the proof that those basic biological changes are actually causing the visible psychological changes we see.

Some of them are very, very suggestive; but it's all circumstantial evidence. There's no direct evidence of any of this. And that's something I tried to explain in my book—that there are so many books that have come out saying teenagers do this because they've got dopamine somewhere; and that we just haven't made that link yet. As you can imagine, it's a very difficult link to make.

Dr. Campbell: We're at the level of correlation, but not at the level of proving causation.

Dr. Bainbridge: I think so. Yes. I think the correlations are very, very good, and very, very suggestive. But that's still all they are.

Dr. Campbell: Remembering that correlation does not equal causation is a really big idea that I try to emphasize from time to time. So, I'm glad you brought it up.

Dr. Bainbridge: Well, it's a very big feature of the teenage brain. You're starting to read more and more about the teenage brain in the media. And correlation is perfectly good, and you can make policy decisions on things like when you open your schools for teenagers during the day and things like that; but it certainly isn't the same as causation.

Dr. Campbell: What about hormones? Where do they fit in?

Dr. Bainbridge: The interesting thing about hormones in all of this is they don't really seem to fit in very much. I don't know if you have a phrase like this in America, but people often claim that what teenagers do is because of their 'raging hormones.' But as far as I could tell, the research that I read suggested that very little of teenage behavior is directly driven by hormonal levels. That includes sexual behavior, and much other behavior as well.

Humans brains in general, compared to many animals, seem quite disconnected from their hormones, surprisingly. And I think this is true of teenagers. I think androgens—male sex hormones—can have a slight effect on behavior. But I think what happens is that many boys have so much androgen in their blood that basically they're maxed out on it, and however it varies isn't going to have any effect on them. It may actually be girls, who are lower down the dose curve, who may respond to varying amounts of it.

Of course, the one way in which hormones do affect teenagers is the hormones drive the changes in their body: They drive their physical changes. And, of course, the teenagers' brains are very, very aware of these physical changes. And so, indirectly the hormones affect the behavior. And I think probably that's a more important effect than the direct effect on the brain.

Dr. Campbell: But you made an important point in the book about the fact that love, for instance, is actually mostly mental.

Dr. Bainbridge: Yes. You hear this cliché that the brain is the human being's most important sexual organ. And it does seem that way when you look at pair bonding, and you look at sexual behavior. So much in humans seems to be focused up into the brain. There seems to be relatively little requirement for hormones at all.

You do see this in men who have to have their testicles removed, say, if they have testicular cancer or something like that. The main adverse effect on them seems to be, obviously, the psychological effect that they've lost the testicles. The hormonal problems seem to be much less.

So much in humans seems to be focused up in the brain. Humans have sex for all sorts of reasons; and occasionally it's to have babies, but very often it's not. And so, they're pretty disconnected from their hormones. I mean, what a ridiculous species: Women don't know when they're fertile, men don't know when women are fertile. There can't be many species who run the system like that.

Dr. Campbell: And people that have abnormalities where they don't actually go through puberty, their brain still matures, right?

Dr. Bainbridge: They do. That's the other thing about humans, is there's a tremendous disconnect between puberty and the brain. Puberty seems to be quite variable. Obviously there are a few people who don't go through it. But in everybody it's very responsive to things like diet. Puberty has gotten a lot more recent in the last few hundred years—presumably because diet has improved so much. And yet, the developmental timings of what's going on in the brain don't really seem to be coupled up to that. And so, it seems to be a fairly independent process.

As I say, obviously there's the indirect effect—the fact that puberty would change the physical appearance of the body, which the brain would then be aware of. But there pretty much do seem to be two independent processes. And actually puberty seems to vary much more in its timing than the development of the brain.

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I want to take a moment to mention our sponsor, Audible.com. Audible has over 60,000 titles in all kinds of genres, including psychology and the mind. Today I noticed that Alva Noë's book, *Out of Our Heads*, has just been released on Audible. You may recall that I interviewed Dr. Noë this past summer for Episode 58.

If you are new to Audible you can download *Out of Our Heads*, or any other title for free by going to audiblepodcast.com/brainscience.

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Dr. Campbell: I want to talk a little bit about the relationship between the teenage brain and behavior. But before I do, I want to go back to this whole pruning idea. It seems from the evidence we have that then what we do while we're a teenager is going to have a big effect on what kind of brain we have when we're an adult.

Dr. Bainbridge: Well, it certainly sculpts the adult brain architecture. The question is, of course, how this correlates with what teenagers are doing all the time. You see teenagers, they're with their friends all the time, they're socializing. They just look like they're learning things. They look like they're learning social skills, analytical skills, linguistic skills—all sorts of skills. And indeed they are.

And presumably the things they do, and the things they learn, and the experiences they have sculpt how they respond to things when they're grown up. Psychologists and psychiatrists are interested in this now. They always used to neglect teenagers. But now they've suddenly gotten interested in them, because they realized this is when we learn many of our behaviors.

But again, finding the link between that and the structural changes that go on in every teenage brain, that link just hasn't been made yet. I'm sure it's there. I'm sure there are structural changes imprinted on the teenage brain as it develops, in

response to what goes on around it. But actually showing that one causes the other is, as you said before, a much more complicated thing to prove.

Dr. Campbell: So, taking into account that most of what we're going to say is based on circumstantial evidence, would you talk a little bit about the relationship between the teenage brain and teenage behavior?

Dr. Bainbridge: Many of the clichés that you hear about teenage behaviors are true, aren't they? One of the ones that's most obvious (and I've certainly seen it in my own daughter, who is now 11; she's just started to do this) is that they have tremendous trouble getting up in the morning. And certainly in the case of my daughter, it happened very, very suddenly over a period of about a week.

This is a very consistent finding. And it's a good example of how difficult it can be to work and to find out what's actually going on in the brain. Many of the studies of teenage sleep have been related to melatonin, which is a hormone secreted by the pineal gland, which developmentally forms from the brain. It's on the top of the diencephalon in the middle of the brain. Weirdly, it doesn't have any direct neural connections with the rest of the brain. It's controlled by a very circuitous route.

But melatonin, as many of your listeners realize, is secreted at night. So, people have taken melatonin samples from teenagers and measured them. They have been looking at the shape of the melatonin curve over the course of the day. And they've started to wonder whether teenagers actually lag adults by a couple of hours; and so when we think it's 8 a.m. they think it's 6 a.m.—something like that.

Now, the problem with this is, melatonin is actually quite an indirect measure of what time the brain thinks it is, because it's not the hormone that tells the brain what time it is. There's a little circuit of cells deep within the hypothalamus—in

the suprachiasmatic nucleus, it's called—and that almost certainly (there's lots of good evidence for this) actually has a little roughly-24-hour clock ticking away in it. It's just a little circuit of cells, and they show undulant activity with a time period of 24 hours.

Now, of course, actually measuring that in a living human teenager at the moment is impossible. But that's the actual clock. That's really the thing which tells them what time they think it is. And so, all the studies that have been done on melatonin are absolutely fine; there's nothing wrong with them. You just have to bear in mind that it's a very downstream effect of our internal clock.

But, again, that doesn't stop you basing policy on it. And certainly I think some schools in the States—and we've just had one do it in the UK, as well—have started to open later; the idea being that the teenagers will be slightly more with it, slightly more awake, if their school starts and ends later. I think the tentative evidence from the States is that the teenagers do better. They did do some controlled studies in the States, and the performance actually improved when they didn't expect the teenagers to get up quite so early.

Dr. Campbell: I guess one of the behaviors that as an emergency room physician I'm particularly aware of is risk-taking behavior.

Dr. Bainbridge: Yes. Risk-taking behavior is very interesting. I feel quite strongly about risk. And we talk about teenagers taking risks. I think it's partly because we don't like children taking risks, and then suddenly teenagers start taking risks.

Risk-taking behavior, of course, is a very important part of human behavior. To succeed in many things you have to take risks. Most of us would never find a sexual partner if we never took any risks. If you can't risk anything going wrong, then often you don't really achieve very much.

And so, I don't think risk-taking behavior is one of these things which is just a result of the teenage brain not working properly. I think it is actually something that teenagers are kind of pre-programmed to do. They're pre-programmed to try things. They're pre-programmed to try risky things and see what happens. And I think that the benefits they gain from assessing risk, experiencing risk, and experiencing the good things and the bad things that can happen as a result of risk, are very important learning processes.

I think the problem comes because teenagers were probably pretty good at assessing risks 15,000 years ago. I think teenagers were probably quite good at assessing risks of things like falling out of a tree, getting swept down-river, getting attacked by a lion—whatever they were doing, wherever they were living.

They're probably not very good at assessing things like driving on wet roads, or taking drugs of uncertain potency, or having unprotected sex when they have no way of telling when somebody has a sexually transmitted disease. I think it's because the risks have changed that the whole thing is going a bit wrong for teenage risk-taking. I don't think it's the teenage brain. I think the teenage brain knew what it was doing, but we changed the risks, and it just hasn't been able to cope.

Dr. Campbell: I know sometimes I wish that I could have a little bit of that boldness back.

Dr. Bainbridge: I think many people do pine after it. I mean many people pine after their teenage years in general. But many of the most successful people you see have taken tremendous risks to get to where they are. And I'm sure for each of them who's been incredibly successful there's another 10 where it's all gone horribly wrong.

I do think risk is important, and I do think it's vital. But one thing you can see very clearly, it's not just teenagers, but adults are also very bad at assessing, and managing, and considering risk in general. So, I don't think it's just teenagers. I think they just suddenly fire up the old risk system.

The other reason, of course, that teenagers take risks is there's a very important psychological process, which is that they have to reject the influence of their parents. And that, or course, makes them want to do things which are seen as bad. And so, that's a little additional reason that teenagers take risks, as well.

Dr. Campbell: What about the moodiness that so many teenagers seem to have?

Dr. Bainbridge: Well, they have very, very intense emotions. My memory of being a teenager is that the good things were really, really good, and the bad things could be really, really bad. It all seemed very intense, and immediate, and vivid. And this is what many people say anecdotally about their own teenage years.

And that often seems to be how teenagers are. I suspect (and quite a lot of the studies suggest this) that what's happening is that, again, early on in the teenage years you get very good at developing emotional reactions, either good or bad. But the bits of the cortex—especially the frontal cortex, which may feed back and damp down these responses—don't necessarily develop quite so early. So, this may be an asynchrony in development of the brain.

There are various theories that are based on things like the social area of the brain develops first, then the emotional area (so you can see the emotional importance of social things happening around you), and then only finally do you develop these cortical areas which feed back and control all these things. And occasionally you do have teenagers who will lash out and have very violent

emotional reactions. And then they'll burst into tears, or become incredibly embarrassed, because they'll suddenly realize what they've done, and that they shouldn't have done it. It's almost like they do have the control valve, but it just doesn't kick in quite quickly enough.

So, people have started to try and follow these theories up by actually doing something a bit more practical and looking at brain scans. One of the areas they've looked at is how teenagers deal with fear; partly because fear is quite a good thing to study, because it's quite localized within fairly restricted bits of the brain which don't seem to do much else.

There's an area called the amygdala—a small almond-shaped structure, very deep in the brain, one on either side—which seems to be very involved in reactions to fearful stimuli; but also memory of fearful stimuli, and also even reacting to fearful expressions on other people's faces. It's a very complex structure. It's not just one blob that all does the same thing. There is lots of internal structure inside it.

When you do functional magnetic resonance imaging on people—when you look at blood flow in different areas of the brain—you actually find that different parts of the amygdala, and even differences between the left and right, react to stimuli different ways at different ages in teenagers, and also as opposed to adults. And they even differ between boys and girls, as well.

If you take something fairly simple to study, like fear (I've said the reason why it's relatively easy, because it's gotten sort of separated out from most other functions in the brain) you do find that there are real functional changes in there. And, of course, fear is very important in our behavior, because fear can lead to lots of things. It can lead to depression and things like that; but it can also lead to anger. And depression and anger are two things that we often characteristically think of as being teenage things.

Dr. Campbell: Getting back to the dopamine pathways—because they seem to be really important—what do we actually know about how these pathways are changing during adolescence?

Dr. Bainbridge: Dopamine is a weird transmitter, because it's involved in a very weird variety of pathways. The main pathways I'm aware of—and none of these pathways seem to have much to do with each other—one has to do with secretion of milk (which has got nothing to do with what we're talking about); another has to do with the control of movement, especially in humans, not so much in other animals (that's the one that's involved in Parkinson's disease, so, again, that's not really what we're talking about now).

But there are two pathways which do seem to be important in teenagers. One is these projections up to the cortex, which seem to moderate and modulate activity, especially of frontal cortex processes. And the other pathway—again, nothing to do with the other three—is the so-called addiction pathway, which has to do with the septal nuclei.

And it's basically the pathway which we think is probably the major common central pathway related to addiction (however you define that; of course, that's quite a complicated issue). So, if we ignore the Parkinson's and the milk secretion, it's really the dopamine projections up to the forebrain, and the so-called addiction-related pathways, which we're particularly interested in.

The dopamine projection pathways up to the forebrain are quite difficult to study, because if things are big enough to study on brain scans—if they're within the resolution of a modern MRI scan—then obviously that suddenly makes them very easy to study. If they're not, it makes them a lot harder, and you tend to be looking at things like post mortem studies, where you just don't get much material. You don't get much material from teenagers—luckily—because hopefully most of them don't end up in the post mortem area.

The addiction pathway is, again, very deep in the brain, very difficult to study in real time. There the information we have about the dopamine pathway of addiction is, again, really different patterns of stimulus-response, looking at how easy or how difficult it is for teenagers to get addicted to different substances; how easy or difficult it is for them to then kick that addiction. And to actually look at some of the differing biological effects of various addictive substances on the brain and the body.

So, there are four dopamine pathways—two not really relevant, and two apparently very relevant. But because these are sort of below the range of discrimination of imaging techniques, we still have to be quite cautious about what we know about these.

Dr. Campbell: What about what you wrote in the book about the difference between the tegmentum accumbens pathway and the tegmentum accumbens cortical pathway? Is that evidence more solid?

Dr. Bainbridge: It is solid; but again it suffers from the same problems. We think the one pathway going to the cortex gradually seems to predominate over the one going to the accumbens—the sort of basic drive pathway. Most of the evidence points in that direction. It doesn't necessarily mean that evidence is complete. And again, as I keep saying, it's important to emphasize that lots of the evidence seems to fit together, but it doesn't mean that all the links have been made.

Dr. Campbell: But what are the implications of that particular evidence?

Dr. Bainbridge: One implication is that addiction is a very complicated process. And it's probably a process that you in your line of work may know more about than I. There are various aspects to addiction, but there does seem to be this pathway involving the nucleus accumbens in the septal region of the brain.

It's a very important pathway, which is why we have it. It's a pathway which appears to program us to seek out things which we have previously enjoyed.

In itself it may not be directly involved in enjoyment, but it's a sort of spin-off. It directs us to seek out things we've enjoyed in the past; which is obviously quite important if those things are food, drink, shelter, sex, or things like that. And this seems to be the pathway into which drugs tap. They kind of push themselves up your list of priorities. As soon as you take something like cocaine, it edges its way up: It super-activates this pathway. It releases lots of dopamine in this pathway, and that makes you want more.

Dr. Campbell: Now, is the tegmentum accumbens pathway the same pathway as the one they think is related to addiction?

Dr. Bainbridge: Yes, it is. And it's involved in, as I say, finding all these things that you've enjoyed before. But addiction is more complicated than just a simple drive to find the same thing again and again. Of course, I suppose you could say that's the basis of what it is.

But you do have conscious control over addiction. We know you have conscious control over addiction because people think, 'I don't want to be addicted to (whatever drug it is,)' and they give it up. This is the cortical pathway—the projections up to the cortex—and cortical activity that allow you to make that conscious decision and to fight this inner urge to take whatever drug you want.

And the possibility is in teenagers that if the accumbens pathway is developed earlier, before the projections that activate the cortex, the idea is that it then makes it harder for them to quit whatever drug they're on. And there is quite a bit of evidence that teenagers seem to find it harder to quit nicotine. Lots of the best data seems to come from nicotine.

It may be true of things like cocaine and alcohol as well, but certainly with nicotine there's quite good evidence that teenagers just do seem to find it harder to give up nicotine than adults do. And maybe this is because there's less of this sort of cortical control—control from above—tempering the accumbens pathway below.

Dr. Campbell: Now, if we leave out the problem of addiction, would the significance of the accumbens cortical pathway over the old tegmentum just to the accumbens pathway mean that we would be able to go from being sort of driven by really basic things—emotional drives—to being able to become driven or rewarded by more mental goals, or whatever?

Dr. Bainbridge: I think it probably is part of this whole process. There used to be this old tradition where they'd say that there's this reptile brain deep inside us, and then built on top of that was the mammalian brain, and then built on top of that was the human brain. But actually most brains have all the same parts in them. And lots of the things that are called 'neo', or new, are actually present in fish and reptiles; it's just not the bits they particularly use.

The thing you do see in humans is this gradual transfer of certain bits in the brain start to predominate and become more important—especially towards the end of the teenage years. And the late teenage years are the triumph of the neocortex, where all this tremendous drive to socialize, and analyze, and self-analyze suddenly seems to come good.

Kids often seem to come good at about 17, 18, or 19, and suddenly seem articulate adult people. It's almost as if they've come out of nowhere. I think that's sort of where the teenage story ends—where it suddenly all comes good. And not much really seems to happen after that. Girls aren't growing any more at that age. Boys have just about stopped growing.

And yet, right then, there's the brain, that's really how it's going to be. And in just a few years the brain has kind of sculpted itself; and especially the way the cortex controls the inner workings of the deeper parts of the brain and near the center of the brain. That in a way is a big part of, I think, what's going on in the teenage brain.

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Dr. Campbell: How does the way that teenagers think change during this period?

Dr. Bainbridge: In the anecdotal evidence (there are quite a lot of psychological studies of how teenagers think and what they do) there are various things that happen. They start to think about themselves less. In the early teenage years there's quite a lot of almost obsessive introspection which goes on—probably more in girls than in boys, but it's a feature of both sexes. And that gradually wanes as they get older, to what we probably start thinking of as a more sensible, more moderate adult level.

Goal-directed learning just continues to become more and more complex. They do the thing which children can't do, which is they're not very good at planning—you know, 'I want to be doing so and so in five years' time, so I've got to do this, and this, and this.' And that just gets better and better. And it may well continue developing into adulthood as well. But by the time you get to 18 or 19, you're really starting to think quite a long way into the future.

Also the way humans think socially changes a lot towards the end of the teenage years. The early teenage years are characterized by a real sort of obsessive need to push yourself away from your parents and interact with people of your own age—to have friends, of course; that thing which, to me, seems pretty unique to humans. And that tendency moderates later in the teenage years.

So, it's very clear that teenagers start being nicer to their parents. And they still have friends, but their friends are kind of different, and it's being moderated more by things like romance and sex. That starts to take up more of their time. And so, I suppose you could say that their social world goes back to being more balanced, rather than just being completely friend-obsessed, as it is early on.

There are a few things that you can measure very specifically, like working memory—how many concepts people can maintain in their brain at any one time. There are some sort of mathematical psychological tests which do this. And you find that the number of things people can hold, basically in the front of their mind, increases pretty steadily throughout the teenage years.

And, of course, being able to think about lots of different things at the same time, that's what leads to lateral thinking, and comparing things, and even creativity. Often creativity is bringing together two things that really wouldn't make sense to be brought together when you're 10, but when you're 20 or so, when you put those two together, then you suddenly get a new interesting juxtaposition.

So, these seem to be the ways that the teenage brain is changing the way it thinks. But, as you can tell from all the things I've been saying, these are really psychological findings. They're not basic neuroscience findings. And so, again we have this gap between the basic neuroscience and the measured psychological changes that we observe.

Dr. Campbell: And even before we started into this current, hopefully golden, age of neuroscience, we had a lot of psychological information. I can remember the first time I heard about the difference between concrete reasoning and abstract reasoning. And you look around and you think,' Huh! There are an awful lot of adults who never make it to abstract reasoning.'

Dr. Bainbridge: Yes, that's one thing that always worried me about psychology—they love having stages that people go through. I think people are more complicated than that. I think some people get good at certain things. Some people are never any good at math; but it doesn't mean they're stupid people, it just means they're useless at math. They may be wonderful at something else. Yes, that would be a big problem with psychologists—that they do like staging human life in a way that I'm not sure really – I think the change is a bit more continuous than that.

Dr. Campbell: What about language skills? We obviously learn most of our language before we reach adolescence.

Dr. Bainbridge: This is a very interesting divide, because, you're right: we seem to learn lots of our language by adolescence. And if by language you mean pronunciation, vocabulary, grammar, syntax, then that's absolutely right. You're pretty good at talking by the time you're 10 or 11. And if you're not, then it's probably a bit too late to do very much about it.

But that's really only the first part. Human language is a wonderful thing; because there's that half of it, and that half in itself, of course, is impressive enough. But because I was writing about teenagers, I had to make out whether the teenage side of it was more interesting. The thing teenagers start to do, is they start to put their language into a social context. And there are various parts of this.

One thing is, first of all, whenever they're going to say something, they think about how the other person is going to react. It's called mentalizing. It's making mental models of what's going on inside other people's heads. Because we all do it all the time, we don't really think about it very much. But, of course, actually it's an incredible, fabulously complex and interesting thing for us to be able to do

—to project ourselves inside other people's brains, and make assumptions about how they work and think, before we speak to people.

The result of this is that teenagers do this thing which children don't. We love children because they're very naïve, and they'll talk to everybody in the same way, whether it's the Queen of England, or their friend at school, or their teacher: They talk to them all the same.

Teenagers very obviously stop doing that. They start talking to different people in different ways. Very characteristically, for example, they monosyllabically grunt at their parents—which often seems to happen here. It probably happens in America, as well. They can be quite articulate and charming with other adults if they want to be; so it's not as if they've lost the ability to speak.

And then the most spectacular is the linguistic changes involved in communicating with other teenagers. When teenagers get in groups, the language they use, I'd say, is probably the most complicated and clever language they'll use all their life: because it's ultra-social language. The idea is it's language to create little social groups—little exclusive social groups—into which children, adults, and some other teenagers cannot get access, simply because they cannot understand the language.

So, the language is slang, and idioms, and in-jokes, and deliberate humorous provocation in a very complex way, which is pretty much incomprehensible to adults. Which I think often makes adults quite cross. But that's just life. It is meant to be there to exclude adults. And, of course, teenage language just gets more and more complicated. Teenagers don't just have one social group. They can have more than one, and they'll use different forms of language with different groups.

And then of course, at the end we have the superimposition of what I think is the most wonderful form of human communication, which is they have to learn how to flirt, as well. Now, if ever there was a complex form of language, it's flirting: A form of language where you're communicating with somebody, but it's very unclear whether they're supposed to know the message you're actually trying to convey. Or are you trying to convey it? And do you want them to know? And how much do you want them to know? I think teenage flirting is far more complicated than adult flirting. I think adults tend to be a bit more direct.

And so, the language changes are very dramatic. It's not the grammar: Well, there's a little bit of extra grammar, a little bit of extra vocabulary you learn when you're a teenager; but I wouldn't expect it would be more than 10% or 20%. The real change is the social context in which you communicate. Because we all learn to do it, we all just take it for granted. You talk to different people in different ways, and you do that because you learned to when you were a teenager.

Dr. Campbell: That's a good point. It sounds to me like teenage language is perhaps an under-researched area. But then I think you make the point that basically teenagers are under-researched—or have been.

Dr. Bainbridge: I think they have been. I think things have improved in the last 10 years. The ability to brain scan has been a huge boon, because you can take one individual and repeatedly look in their brain—for 10 years if you want to. Psychologists have suddenly gotten interested in them, at last.

People who have developed social policy have become interested in them as far as why do they become involved in crime, why do they become involved in addictive substances, and things like that. When I was writing this book, so much of what was in it had just come out in the last 10 years. It was very striking.

Dr. Campbell: From a cognitive standpoint is there anything that teenagers do poorly that sticks out in your mind?

Dr. Bainbridge: I think the ability to hold lots of things in their mind at any one time—the working memory—that did quite impress me; partly because it's a very objective, tangible test which you can use on humans and measure how many things they can hold in their mind at any one time. And you can measure it increasing. Of course, in teenagers, because of the way their brains work (they're almost free-running; they don't have many inhibitions, they don't have many assumptions, because they haven't got much experience to base them on) they can hold all these things in their heads, and put them together in all these weird orders.

Many of the great human flights of creativity that have really made the difference to us, I think have often been based on ideas which people have had when they were teenagers. I don't think they could necessarily exploit them fully when they were teenagers, because they didn't have enough experience or skill yet.

People like Einstein, many writers, many artists, although they didn't necessarily produce the work when they were teenagers, would often hark back to ideas or thoughts that they'd had when they were teenagers. So, the teenage creativity, I think, is very important, even though they often don't seem to do anything tangible with it.

Dr. Campbell: Do they have trouble with interpreting the emotions of non-teenagers?

Dr. Bainbridge: I don't actually know. I haven't really looked into that. I think to a great extent they're not very interested. So, I don't know if it would necessarily worry them. But I don't know if they find it harder to interpret. I

think they're very good with each other. I just don't know if they really focus on other people very much.

Dr. Campbell: OK. Well, we're just about out of time, but I want to ask you, first of all, do you have any specific advice for parents?

Dr. Bainbridge: I think it's the same as with many things that you find difficult in life. Teenage behavior—they all do it; you just have to accept it. I think the thing that the brain and the evolutionary story tells us is that adults may have been put on earth to make life easier for teenagers, but the opposite is not necessarily true.

Dr. Campbell: OK. What about specific advice for teenagers?

Dr. Bainbridge: Again, teenagers can be great, they can be awful. They are just very vivid. Despite what other teenagers may say, everybody is going through the same basic process: Try and make your own decisions as much as you can.

Dr. Campbell: And I think you also (we won't have time to get into this) made a good case for putting off experimenting with things like drugs and alcohol.

Dr. Bainbridge: Yes. I was very liberal about this before I started writing the book. But the more I looked at the evidence—especially with the very potent drugs that are available nowadays—it just worries me what the possible effects could be of substances like that hitting the brain in this very sensitive developmental phase. Like I say, I was very liberal about drugs before I wrote this book; but I just do wonder if it might be best waiting to try those things until you're a little bit older.

Dr. Campbell: Is there anything else you'd like to talk about before we close?

Dr. Bainbridge: I think that's pretty much it, really, because I don't want to move over into the non-brain stuff; because that's a whole other kettle of fish, really.

Dr. Campbell: Do you see teenagers as being a potential audience for your book?

Dr. Bainbridge: We discussed this when we were first pitching the book. It would have been lovely to write the book expressly for teenagers, but my publisher—very sensibly, I think—pointed out that most of these sorts of books are bought by adults. I have had quite a lot of feedback from teenagers whose parents have bought the book, and they've then gone on to read it.

Most of the feedback has actually just been saying it's nice that somebody has written a book that's quite nice about teenagers for a change, rather than just complaining about all these awful things they do. I don't know what it's like in the States, but the media over here is just full of bad things that teenagers are doing. They never talk about any of the good things.

Dr. Campbell: I think it's pretty similar here.

Dr. Bainbridge: Yes, I'm sure it is.

Dr. Campbell: I was wondering, because I couldn't figure out after reading the book (I don't have any of my own kids, but I have teenage nieces and nephews) whether or not they would actually read such a book. It's hard to tell.

Dr. Bainbridge: I think really it would be later teenagers who would read it, in general. I've had a few early and mid-teens. My daughter started reading it. She's read snippets of it. She's only 11, so she's had to jump over a few bits. But I think she quite liked it. I mean I think she was just reading it to find out what the hell is going to happen to her.

Dr. Campbell: Yes. And for those of you out there who are teenagers, this book answers the question, 'Do girls really mature faster than boys?'!

Dr. Bainbridge: Oh, yes. That's the all-important one; especially when you're a 13-year-old boy—as far as I can remember, anyway.

Dr. Campbell: But you have to read the book to find out the answer!

Well, David, I really appreciate you coming on the show. And I want to also thank you for writing *Beyond the Zonules of Zinn*, and sharing your images from that book. That's one of the episodes that people either love or hate, depending on where they're coming from.

But I've gotten some good feedback from it. And I think it's a great book. And I've had a lot of people tell me that they bought it; so, I hope that helps a little.

Dr. Bainbridge: Yes, I've certainly had quite a lot of feedback from people who've read the book via listening to your podcast. So, I know it's the right audience for me.

Dr. Campbell: Well, great. I'll let you know, David, as soon as this show goes up online.

Dr. Bainbridge: That will be great.

Dr. Campbell: OK. Thanks a lot for being on the show.

Dr. Bainbridge: I've really enjoyed it.

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I want to thank David Bainbridge for coming on the *Brain Science Podcast*, and I also want to thank listener Jeff King for helping to edit this episode. I highly recommend David's books—especially *Teenagers: A Natural History* and *Beyond the Zonules of Zinn*, which is the one that I covered back in Episode 32.

I also want to take a moment to thank those of you who are helping to support the *Brain Science Podcast* with your donations. If you are interested in learning how you can help support my work, just go to brainsciencepodcast.com and click on the tab at the top of the page labeled Donation and Subscriptions.

Remember that every little bit helps. Even if you can't afford to contribute money, you can still help promote the show by sharing it with others.

Before I get into today's announcements, I just want to remind you to visit the website, brainsciencepodcast.com. There you will find show notes, links to David's website, and even a transcript of today's episode.

I would love to hear your feedback. You can send me email at docartemis@gmail.com, or join the Discussion Forum at brainscienceforum.com.

And don't forget the brand new phone-in line, 206-984-0358. This line uses a free answering service called K7. When you call this line it will record your message and send it to me as an audio file. Unless you indicate otherwise, I will assume that you are giving me permission to use this audio on a future show.

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Starting this month the *Brain Science Podcast* is coming out on the second Wednesday of each month, and *Books and Ideas* will be coming out on the fourth Wednesday (though I might bring out *Books and Ideas* a couple of days early in November and December, to avoid Thanksgiving and Christmas).

The current *Books and Ideas* is from the live show that I did at this year's Dragon*Con in Atlanta. Les Johnson from NASA was a wonderful guest. You can find that at booksandideas.com.

The November episode of *Books and Ideas* will be an interview with Sheril Kirshenbaum, co-author of *Unscientific America: How Scientific Illiteracy Threatens our Future*; and that will be out before the end of November.

The December episode of the *Brain Science Podcast* will be our Annual Review Episode. And I also have a special episode planned in December for *Books and Ideas*.

I am going to end by telling you a little bit about the new *Brain Science Podcast* application, which is now available in the iTunes apps Store. I have saved this for the end so that those of you who don't have an iPhone or iPod Touch can fast-forward to the end.

I've already gotten messages from people asking me about whether or not this application is available on other platforms like the Blackberry and the Zune. But at the present time this is an iPhone, iPod Touch only application.

First I want to thank Wizzard Media for creating this application. While I have done a lot of work to make sure that you can get extra content (like episode transcripts) delivered directly to your phone or Touch, I would never have been able to find the time to create this application from scratch—or even find time to learn how to write an application.

The price is $4.99 in U.S. dollars. This is split between Apple, Wizzard, and me.

But why would you want to buy this application? First of all, it allows you to listen to any episode of the *Brain Science Podcast* without downloading it to your phone. In other words, you will be streaming it. You can also read the episode transcripts directly on your phone.

Another neat feature is that there are buttons that make it easy for you to send me feedback via email, or the new phone line, or to just go straight to the website if you want to check out a link. I have tested all these features, but I hope you will let me know what you think.

One thing I noticed was that the streaming worked great with WiFi, but not so great on 3G. My experience with other streaming apps has been that they also don't work very well with Edge. Obviously, if you're going on a long trip where you may not have a consistent signal, you will want to download the episodes via iTunes.

I don't really see this application taking the place of iTunes, but it will be useful when you're away from your computer, since it allows you to get around the fact that iTunes won't let you download podcasts over the network if they're over 10 Meg, and the average *Brain Science Podcast* is over 20.

There's one other feature that's kind of cool, called Background Play. You'll find that under Episode Extras. This allows you to continue listening even if you leave

the app, so that you can do things like answer your email, or even your phone. This feature has a few interesting little quirks that I think you'll enjoy exploring.

I don't expect to make a lot of money from this application, but I am hoping that it will generate some visibility for the show. That's why I'm trying to encourage as many people as possible to buy the app during the week of November 9th through 15th.

Then next week I will be promoting a similar app for *Books and Ideas*. I hope you will check it out, even if you miss the official launch week. Be sure to leave a review on iTunes. And I will keep you posted when new features are added.

That's it for this month. Thanks again for listening, and I look forward to talking to you again very soon.

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Transcribed by Lori Wolfson
All errors or omissions responsibility of the transcriber